

# **Shock Wave Propagation due to Methane-Air Mixture Explosion and Effect on a Concrete Enclosure**

Sharad Tripathi, T.C.Arun Murthy, Alain Hodin, K.Suresh, Anup Ghosh

Transoft International

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## § 1. Introduction

Analysis of major hazards in the Industry shows that vapor cloud explosions are mainly linked to deflagration process, leading to subsonic flame propagation. However, in some very rare and specific environmental conditions, detonation can be generated, according to the DDT process. In these cases, high generated overpressures can affect the stability of structural civil works and eventually collapse them.

The aim of this paper is to show the ability of a CFD model to calculate the propagation of a shock wave modeled by an instantaneous energy release in a confined area obstructed by obstacles and to determine the interactions with the structures in the area.

The simulation deals with the explosion of a mixture of methane and air within a concrete enclosure. The structural geometry consists of a rectangular concrete slab supported by reinforced concrete columns. The explosion is due to ignition of stoichiometric mixture of methane and air, considered as a highly energetic release.

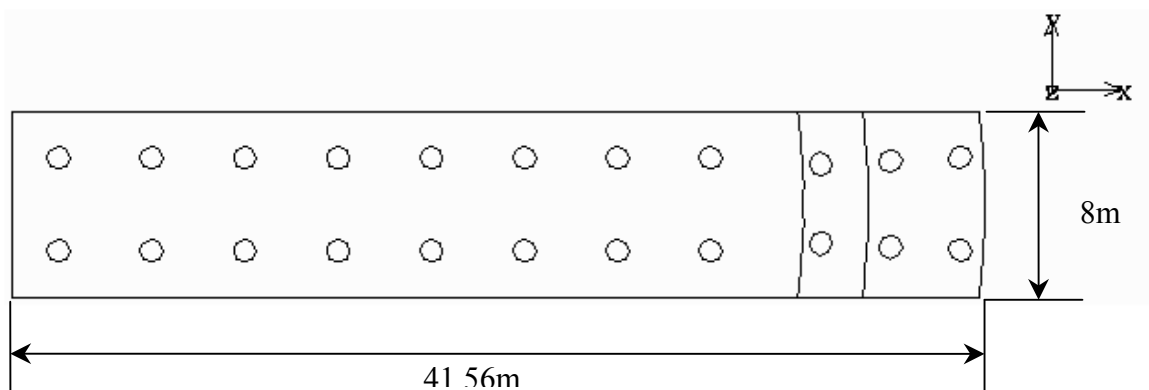
The pressure shock wave propagates into air and concrete with different velocities. Presently the case is simulated as a detonation case. Modified JWL equation of state, dealing with gas specificity is used to model detonation. The objective of the study is to evaluate the detonation pressure and the tension failure of the concrete structure.

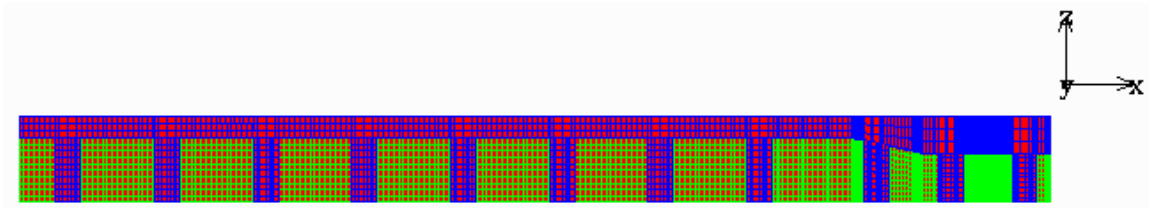
## § 2. Software Used

*fluidyn-FSI*, a multi-physics code for fluid flow analysis, structural dynamics and fluid-structure mechanical/thermal interaction, has been used for the analysis. Finite volume scheme is used for the analysis of fluid flow and finite element analysis is used for nonlinear transient stress analysis in solids. In the coupled analysis for fluid-structure interaction, boundary condition data is exchanged between the fluid and structure continuously. Fluid pressure is transferred to the structure as a force boundary condition, while the deforming structure influences the fluid flow as a moving boundary. A remeshing module is used in this phase for auto adaptive remeshing of the fluid domain following structural displacement. The weak coupling offers great flexibility in deploying diverse numerical techniques for fluid flow analysis and structural stress analysis.

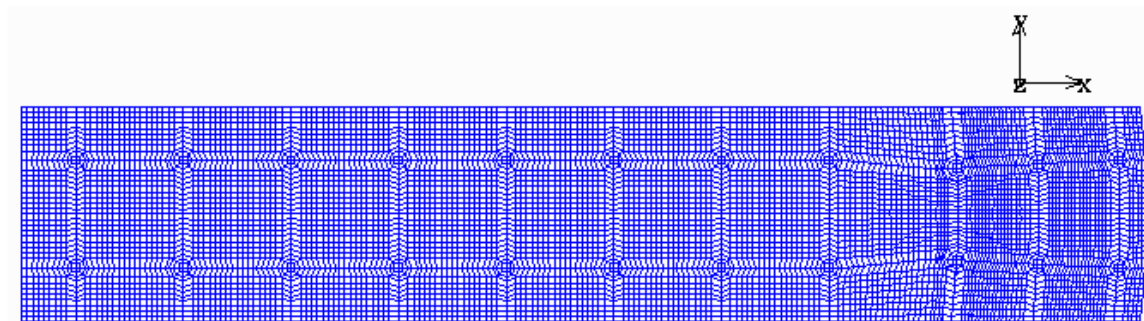
## § 3. Simulation Model

The geometry of the fluid and structure is modeled using 8-noded hexahedral elements... In the present study, 70400 and 26840 hexahedral elements are used to model the fluid and structural domain respectively. Transient simulation is done. Figure 1 shows the outline (top view) of the geometry considered for analysis. The 22 circles show the location of concrete columns. Figures 2a-2d show the mesh used for discretisation

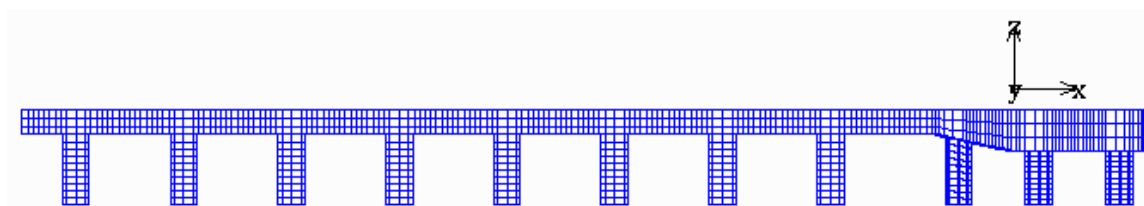




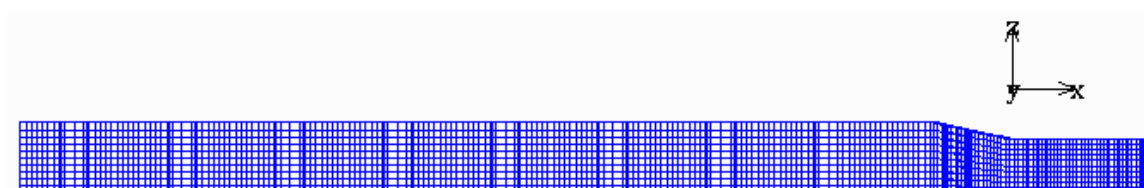
**Fig 2a: Concrete (blue) and air (green) mesh considered for the study.**



**Fig 2b: Top view of Mesh.**



**Fig 2c: Front view of the structure mesh.**



**Fig 2d: Front view of the Fluid mesh.**

### § 4. Boundary Conditions:

**FLUID:** Supersonic outflow condition is imposed on the vertical boundary faces (Fig 3). The fluid boundary faces at the fluid-structure interface (bottom of the concrete slab and surrounding the pillars) automatically follow structural displacement. The remaining boundary faces are assigned symmetry condition. The ignition point is at one end ( $X=0$ ) as shown in Fig 4.

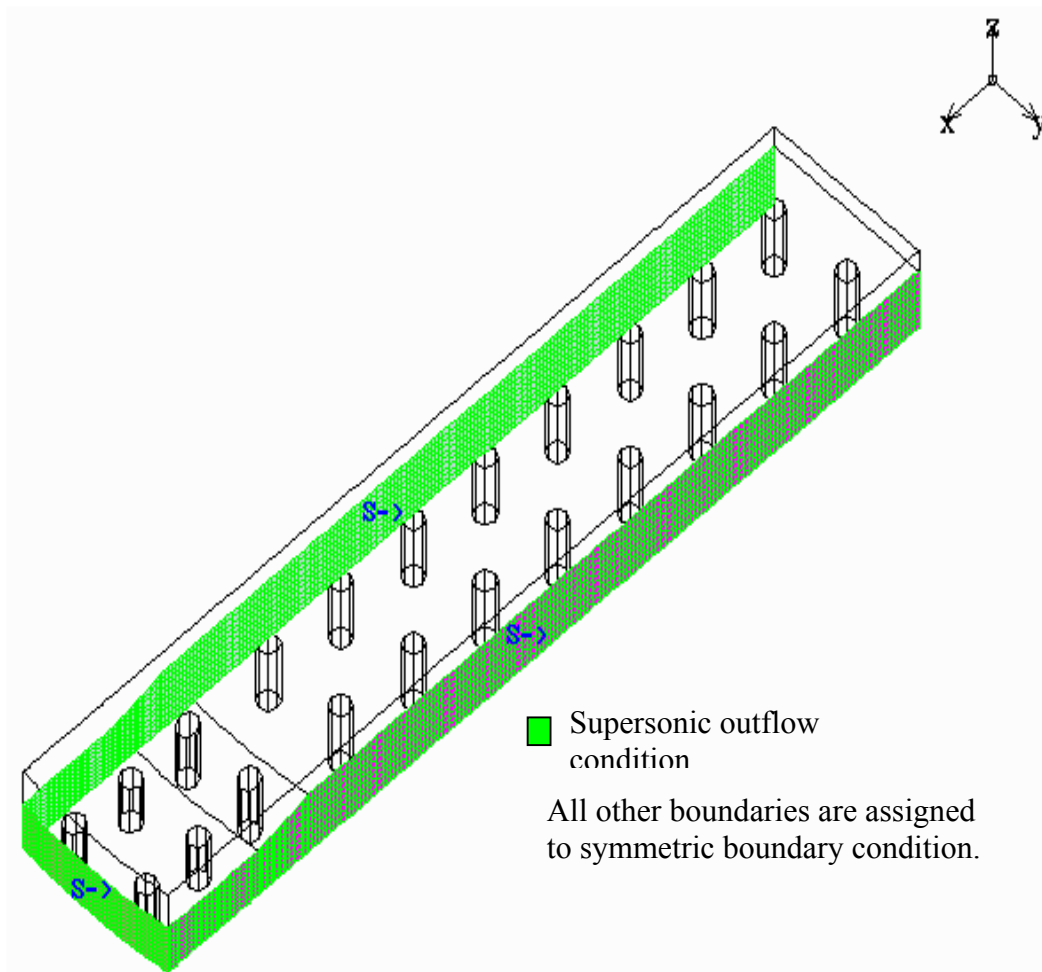
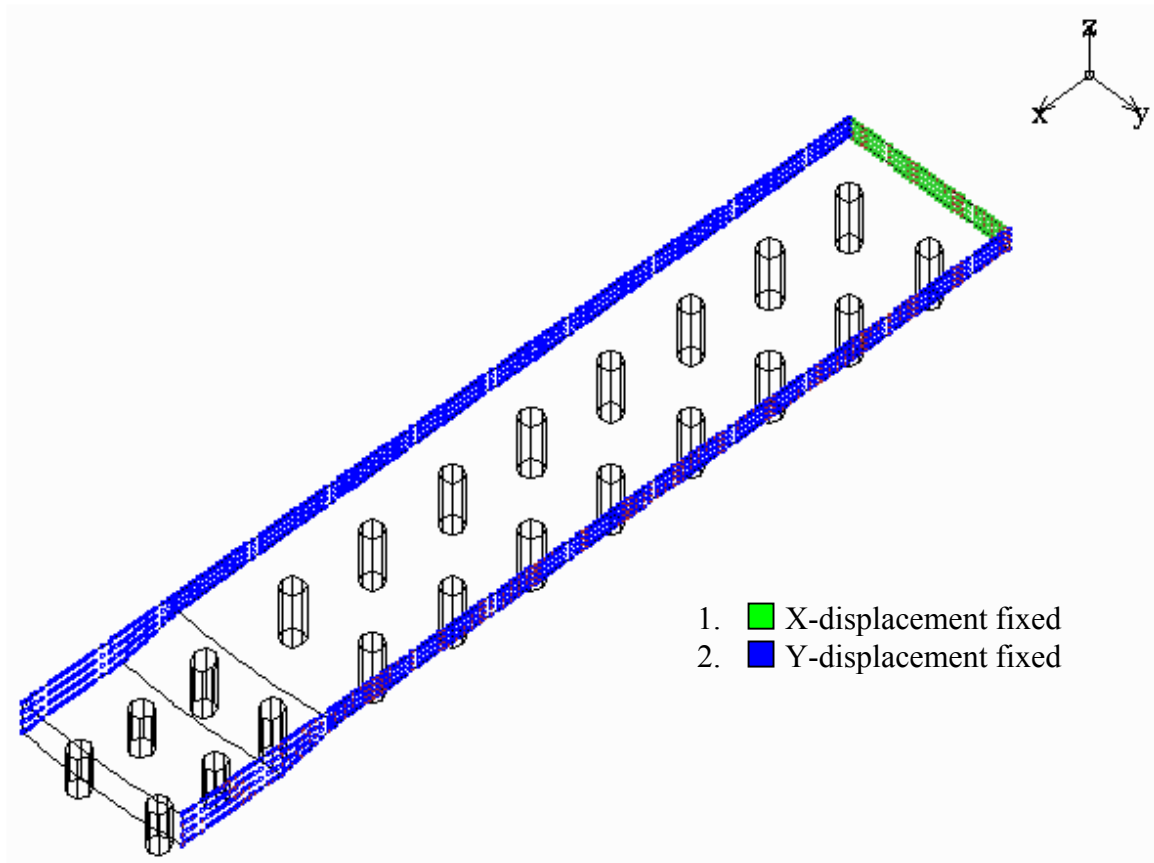


Fig 3: Boundary Conditions on the fluid.

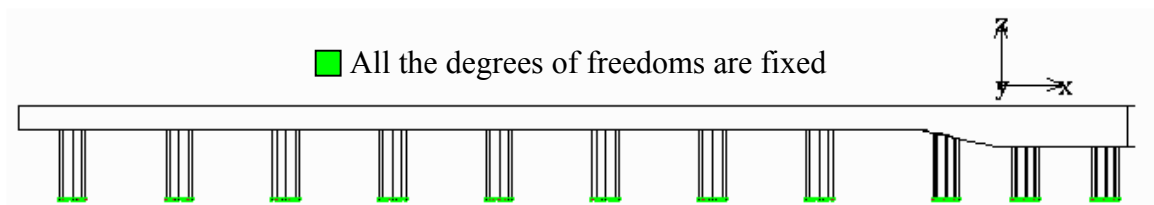


Fig 4: The ignition point.

**STRUCTURE:** The structure is fixed at the bottom of pillars. Planar symmetry is considered by fixing the Y-displacement of nodes on the extreme Y-planes. In addition, X-displacement is fixed at one end,  $X=0$ .



**Fig 5(a): Boundary conditions at slab.**



**Fig 5(b): Boundary condition at column**

## § 5. Concrete Failure Criterion

The following failure criterion has been considered for concrete. An element is considered as failed if the *hydrostatic pressure in the element is less than a specified tensile limit* (or equivalently, the negative of pressure exceeds a limit). Once failure has occurred, pressure may never be negative and the deviatoric stress components are set to zero.

## § 6. Initial Conditions

The concrete structure is initially at rest

The fluid domain is initialized with the following values:

$$\text{Density} = 1.1195 \text{ Kg/m}^3$$

$$\text{Energy release} = 309559 \text{ J/kg}$$

$$\text{Velocity} = 1 \text{e-}6 \text{ m/s}$$

## § 7. Explosion wave propagation Properties (Stoichiometric mixture of Methane +Air) and location

Study shows that when the explosion wave is travelling, local pressures due to shock reflection from columns will be very close to the detonation front pressure. Though it is generally agreed that initiating a detonation front in methane + air is very seldom, it can be safely assumed that the pressure front may travel at the velocity akin to that of detonation.

$$\text{Available Energy} = 1.52 \text{ MJ/m}^3$$

$$\text{Load Density} = 1.1195 \text{ kg/ m}^3$$

$$\text{Static Overpressure} = 8.1 \text{ bar}$$

$$\text{Gamma} = 1.28$$

$$\text{Pressure wave Velocity} = 1802 \text{ m/s (same as detonation front velocity)}$$

Ignition point: 1.01m above the ground level and at the end of the domain of the study.

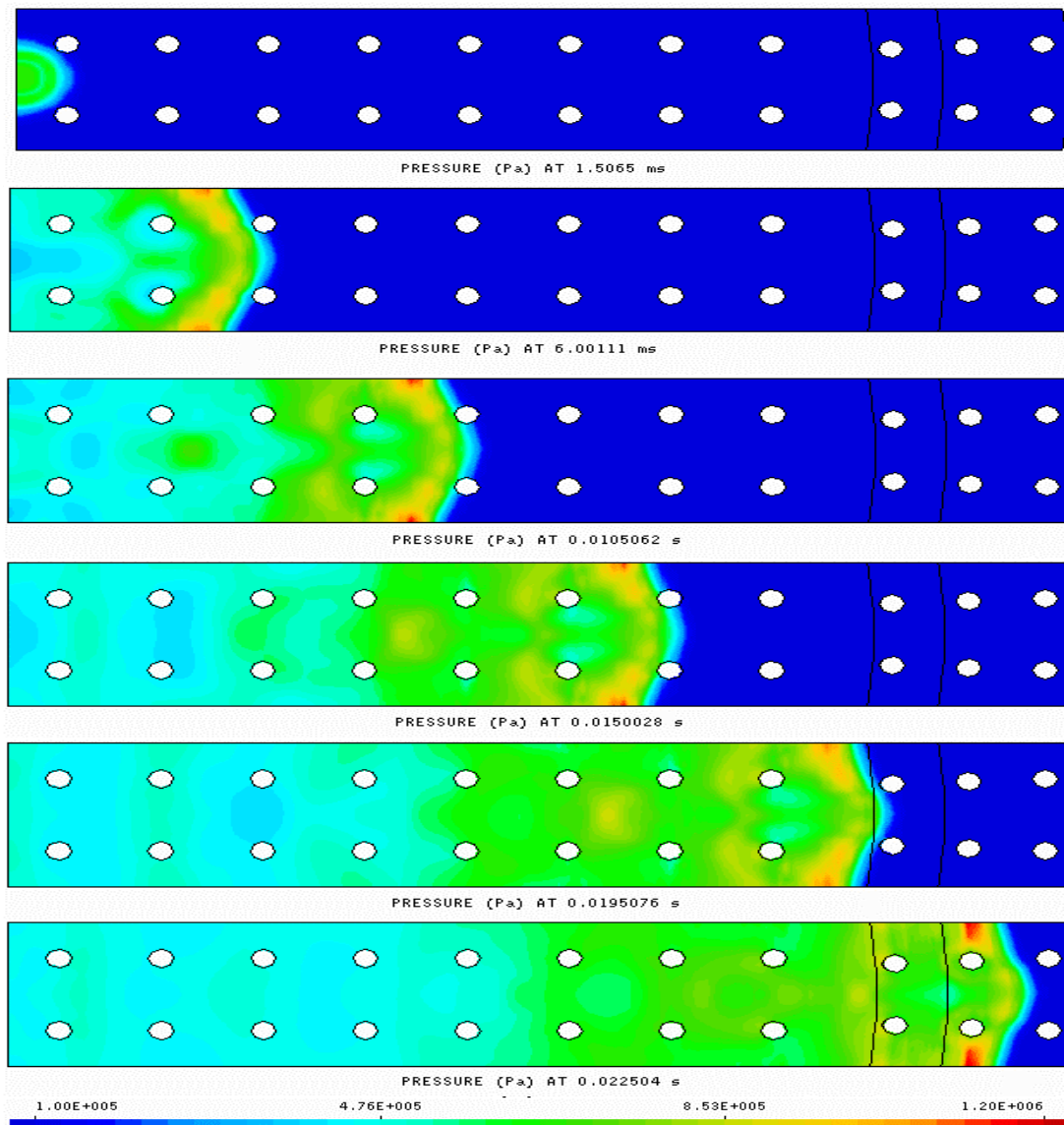
## § 8. Material Properties

	Concrete Slab	Concrete Column+Steel Reinforcement
Elastic Modulus, GPa	40.5	34.6
Poisson's Ratio	0.3	0.3
Density, Kg/m <sup>3</sup>	2400	2400
Yield Stresses, MPa	4	4
Tensile Limit, MPa	3.6	25

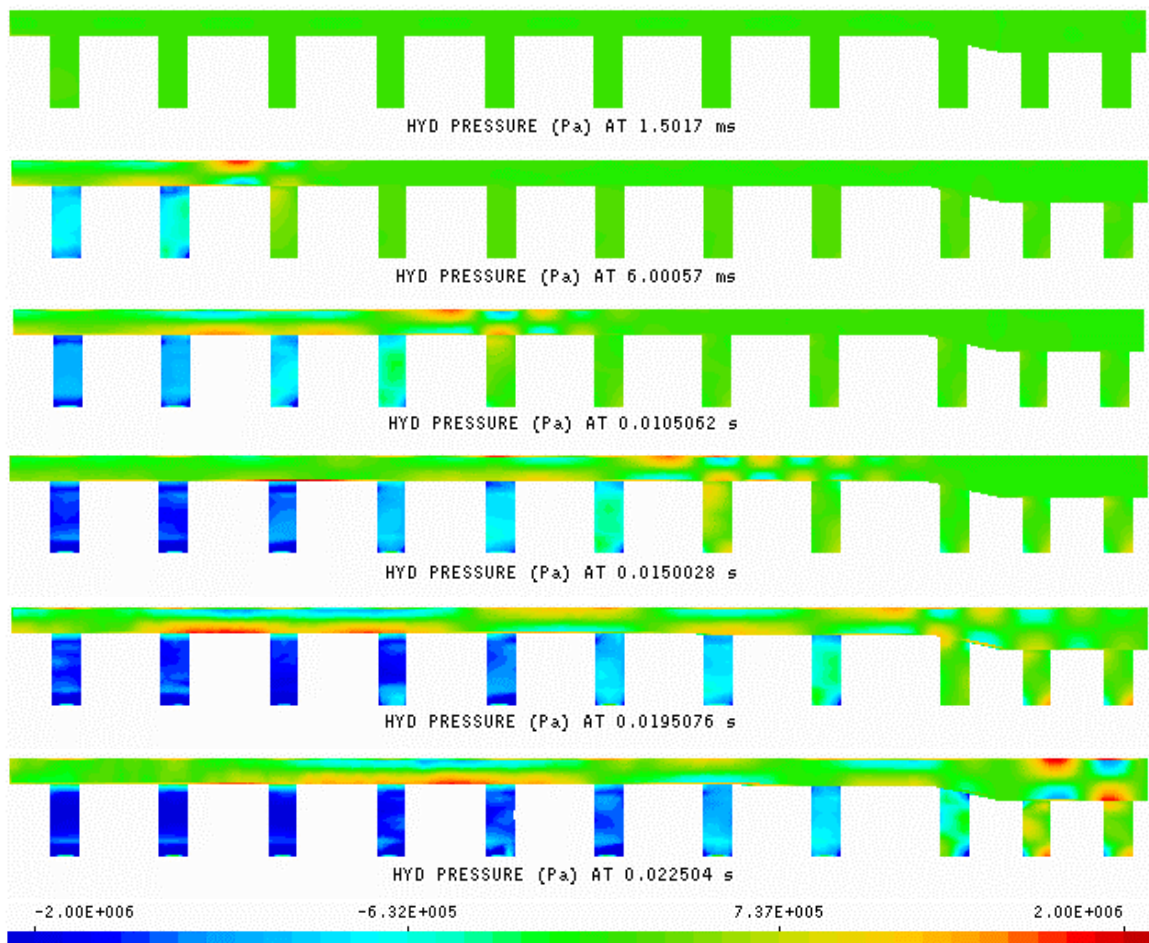
For simplicity, steel reinforcement in concrete is modeled using an equivalent Elastic modulus, 34.6 GPa, for the concrete.

### § 9. Results and Discussions

The series of pressure contours in Fig 6(a) show propagation of pressure wave in the fluid (air + methane). The pressure wave is travelling at 1802 m/s velocity in the fluid. A pressure rise is seen when the wave hits a column. The maximum pressure inside the fluid is observed to be 1.57Mpa, very near the detonation pressure.



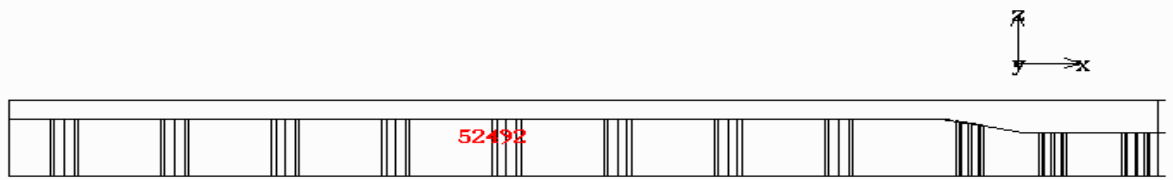
**Fig 6(a): Propagation of pressure wave during the explosion process of the Air and Methane mixture at the top layer of the fluid.**



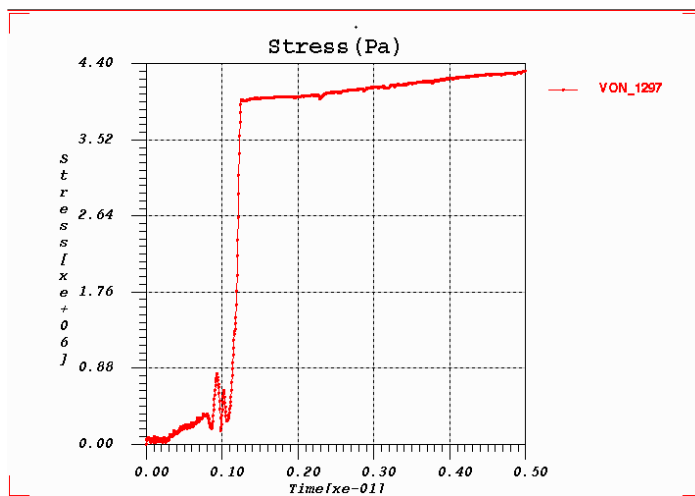
**Fig 6(b): Propagation of hydrostatic pressure during the explosion process of the Air and Methane mixture at the concrete slab and column.**

Fig 6(b) shows the hydrostatic pressure in the structure. The correspondence between the hydrostatic pressure in the structure and the pressure in the fluid may be observed.

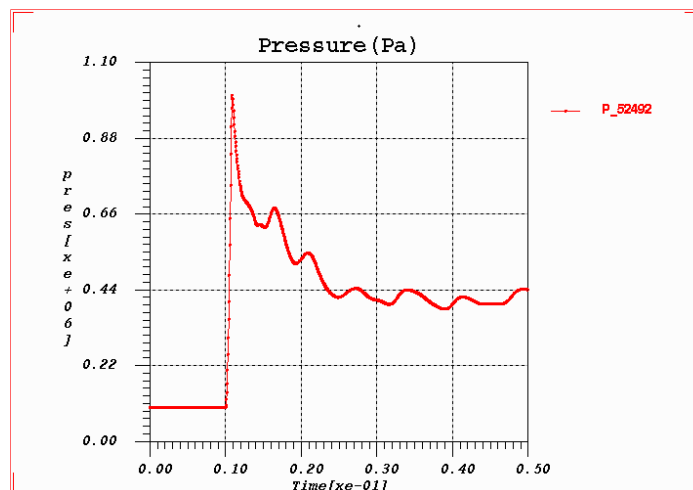
Fig 7 shows the location of a trace point (structure node 1297/fluid node 52492) 17.5m from the ignition point. Stress/Pressure traced at this point is shown in fig 8a-8b.



**Fig. 7: The reference location for the trace plot of pressure.**

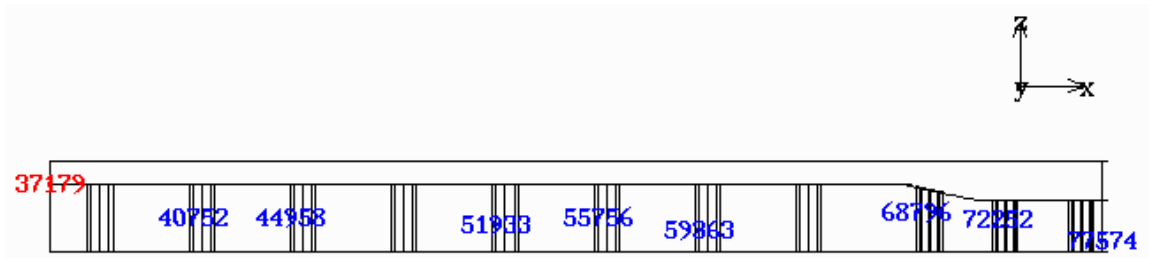


**Fig 8(a): The variation of stress in the structure node (1297)**

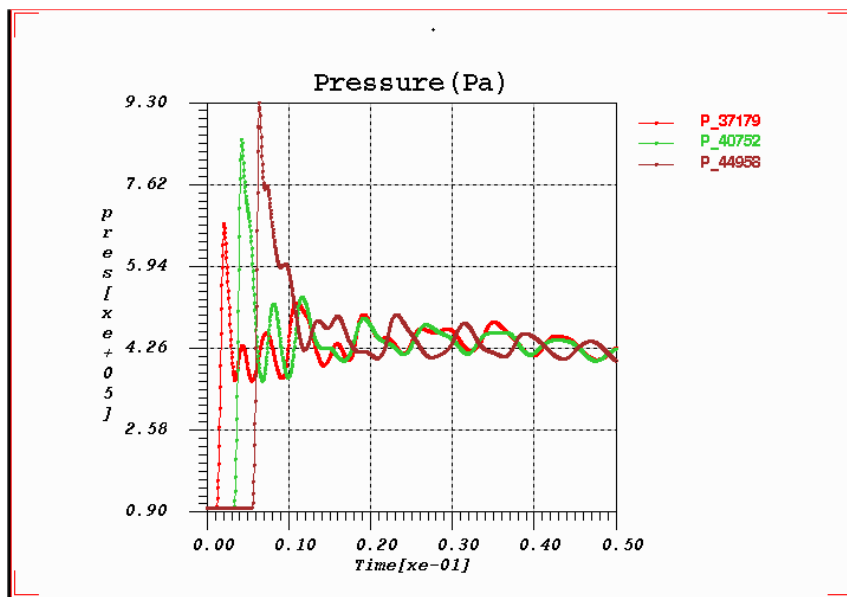


**Fig 8(b): The variation of pressure in the fluid node (52492)**

Fig. 9 shows fluid trace points adjacent to the columns of the concrete structure. Subsequent figures (Fig 10a-10c) show the variation of pressure at those points in the fluid domain.



**Fig 9: Trace points in the fluid adjacent to the columns.**



**Fig 10(a): Pressure trace plots at the monitor points [Time (Sec), Press (Pa)]**

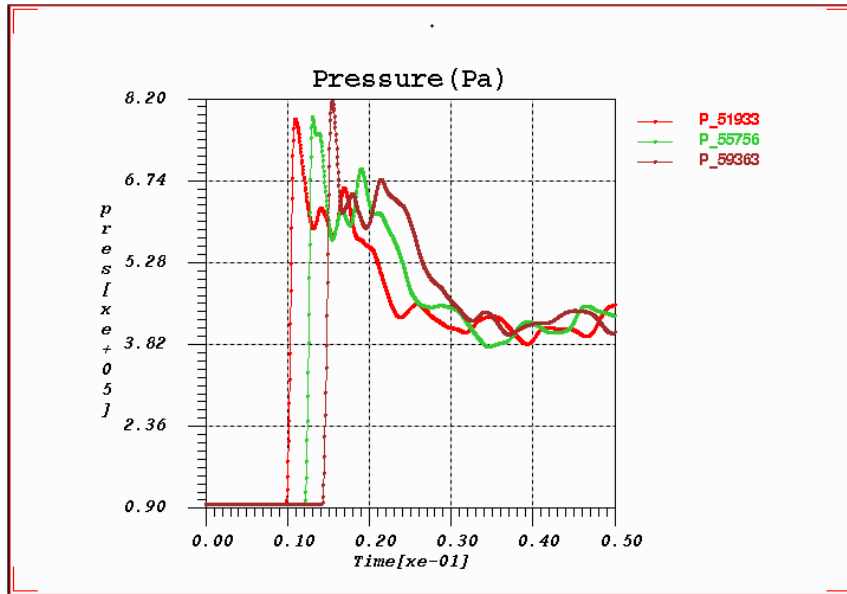


Fig 10(b): Pressure trace plots at the monitor points [Time (Sec), Press (Pa)]

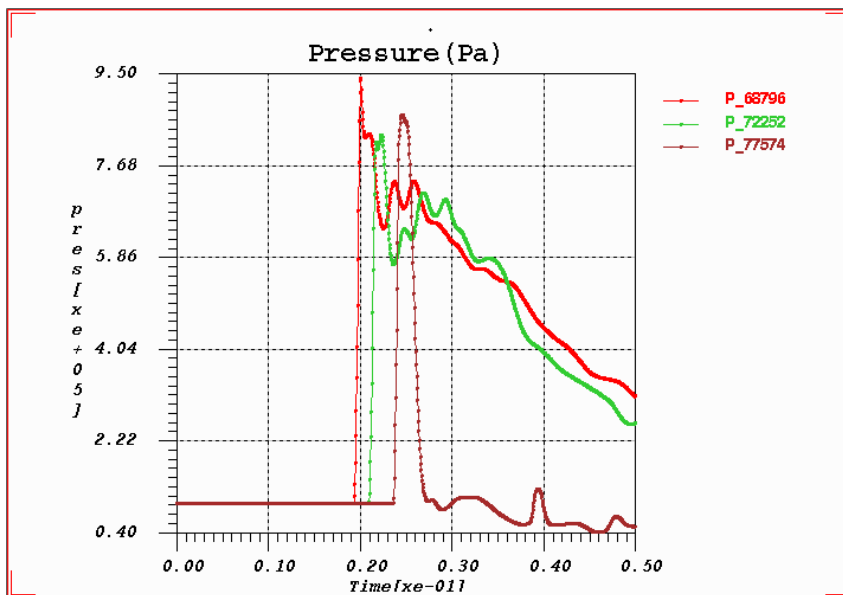


Fig 10(c): Pressure trace plots on the monitor points [Time (Sec), Press (Pa)]

Fig 11 shows the location of trace points on the concrete columns where the Von Mises stresses are traced. Fig 12 indicates tension failure of elements at the selected locations.



Fig 11: Trace points in the columns.

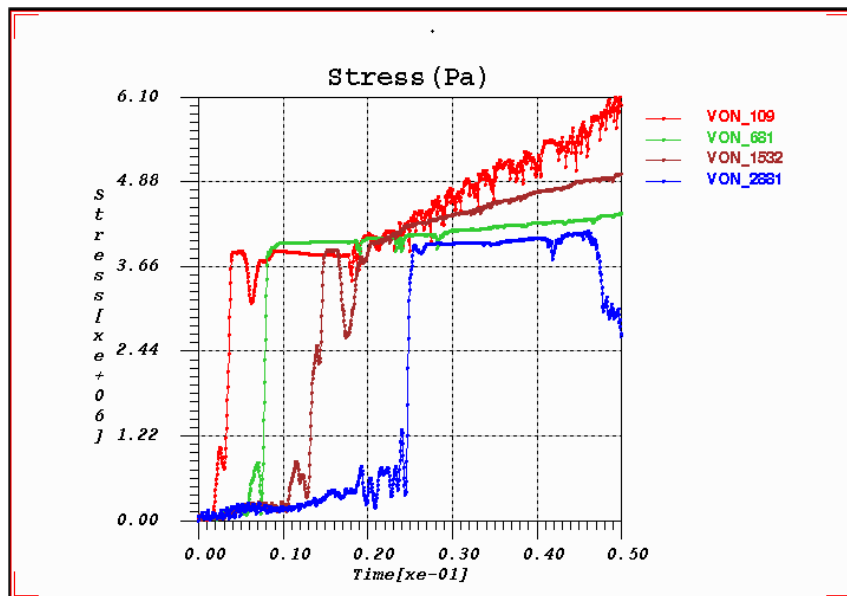


Fig 12: Stress trace plots on the monitor points of the column [Time (Sec), Press (Pa)]

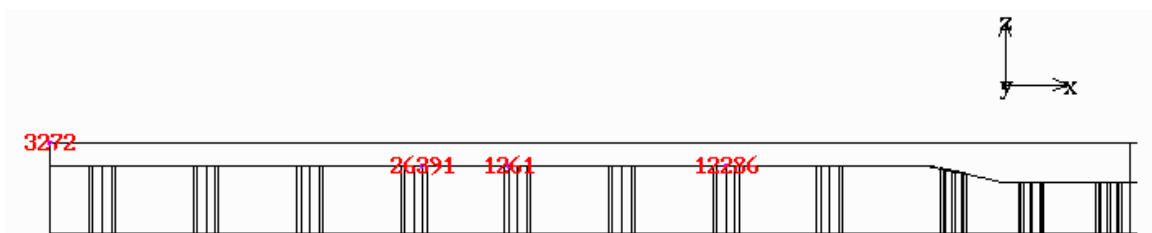


Fig 13: Trace points in the slab.

The Von Mises stress at selected trace points in the horizontal slab (Fig 13) are shown in Figs 14a-14b. The initial stress peak corresponds to the stress wave arrival at that location that has traveled through *concrete* and the second stress peak corresponds to the arrival of pressure wave in the *fluid* at this location.

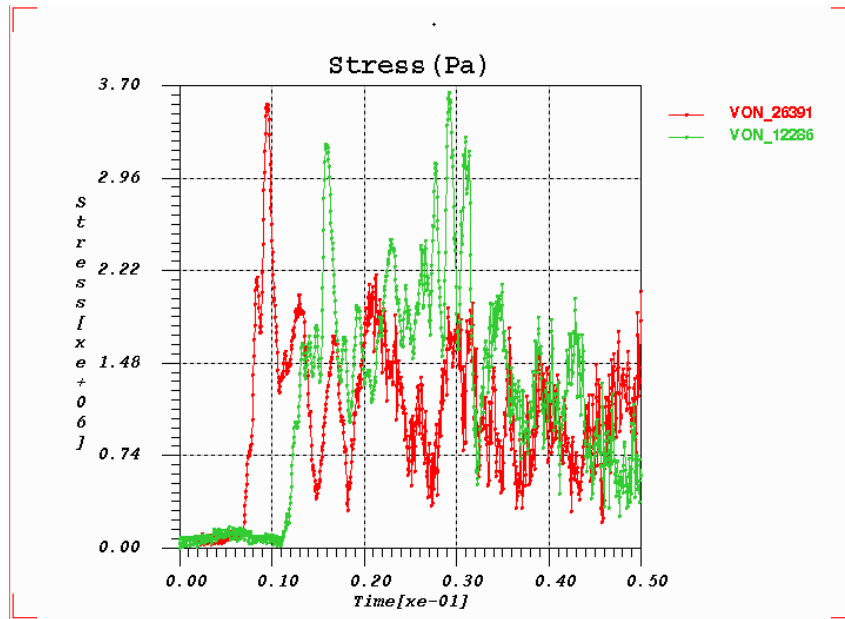


Fig 14(a): Stress trace plots on the monitor points of the slab [Time (Sec), Press (Pa)]

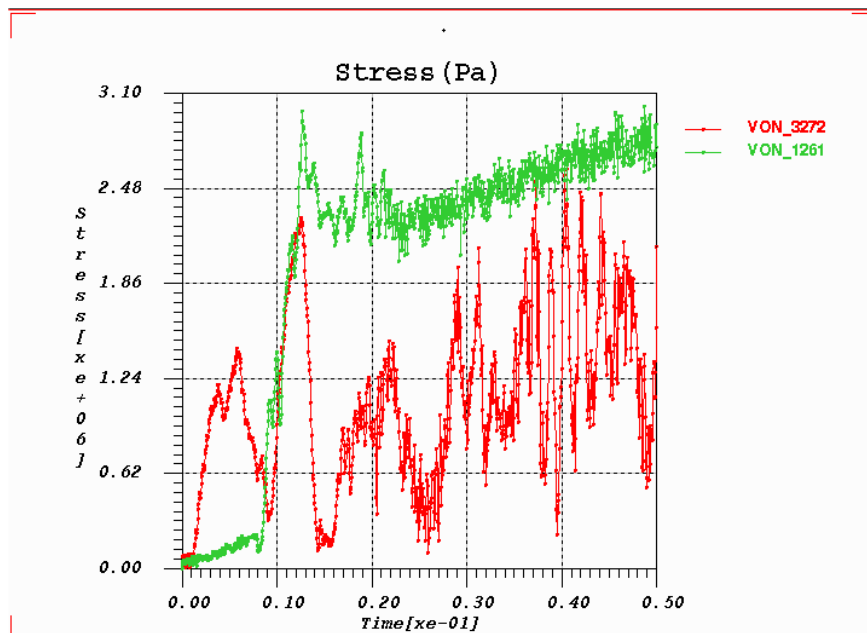
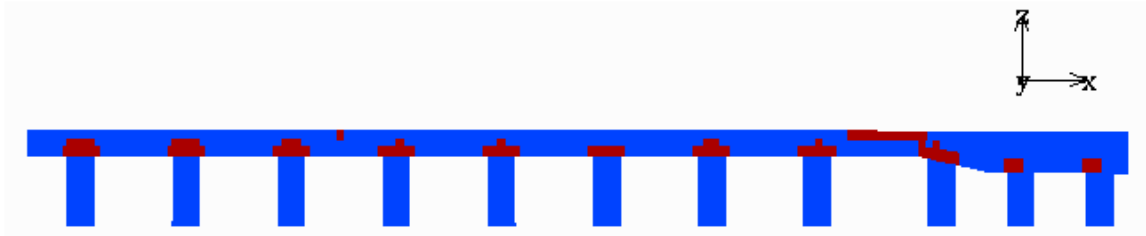


Fig 14(b): Stress trace plots on the monitor points of the slab [Time (Sec), Press (Pa)]

### Status of the concrete structure.

Fig.15 shows the structural elements failed during the explosion. It is observed that the junctions of the columns and the slabs are more affected due to the explosion.



**Fig. 15: The status of the structure at the end of the explosion.  
The red elements have been failed during the period.**

## §10. Conclusion

The initiation of the explosion of the gas mixture and the consecutive propagation of the pressure wave is modeled. In this fluid-structure interaction study modified Jones-Wilkins-Lee (JWL) Equation of State is used to simulate the explosion phenomena. Failure of concrete element is modeled using tension failure criterion. For simplicity, the reinforced concrete slab and columns are represented through the modification of the strength properties of concrete considering the modular ratio of plane cement concrete and steel.

Some representative results show the pressure in the fluid and the corresponding stress in the concrete structure. It is observed that the reflections of the pressure wave from the columns increase the pressure in the fluid near the slab-column junction (Fig. 6(a)). The pressure developed due to the explosion develops tension in the columns. Due to the combined effect of the increased pressure in the slab-column junction and development of the tensile force in the columns some of the junction elements fail (Fig. 15).

The study demonstrates the capability of *fluidyn-FSI* in simulating the fluid-structure interaction. Though a simplified model for reinforced concrete is used in the study, the steel reinforcements may be modeled separately using beam elements with elasto-plastic material properties. A more accurate formulation using the smeared crack approach to model initiation and propagation of crack in reinforced concrete is under implementation in the code.

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