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Numerical Investigation of Sandwich panel Under Blast Loading With Fluid-Structure Interaction

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Abstract* - *Blast-resistant lightweight structural systems have become increasingly important due to the growing risk of accidental explosions, industrial hazards, and intentional blast-related threats. Sandwich panels with honeycomb cores offer an efficient combination of high stiffness, low weight, and superior energy absorption capability. This study presents a numerical investigation of the blast response of honeycomb sandwich panels using Fluid–Structure Interaction (FSI) modelling in ABAQUS/Explicit. A Coupled Eulerian–Lagrangian (CEL) approach was adopted to simulate the interaction between the blast wave and the sandwich panel under varying fluid fractions ranging from 0% to 100%. The sandwich panel consists of metallic face sheets and a honeycomb core modelled using the Johnson–Cook plasticity and damage formulation to capture strain-rate-dependent behaviour under high-speed dynamic loading. The influence of fluid fraction on displacement response, stress distribution, pressure attenuation, and energy dissipation mechanisms was investigated. Results indicate that the presence of fluid significantly alters blast-wave propagation and reduces peak deformation through hydrodynamic damping and added mass effects. Intermediate fluid fractions showed improved blast mitigation performance by balancing pressure attenuation and structural flexibility. The study also evaluates energy partitioning between internal energy, plastic dissipation, and frictional dissipation to identify dominant energy absorption mechanisms. The developed numerical framework provides insight into the design of lightweight blast-resistant sandwich structures for marine, defence, and civil engineering applications.

Keywords - Blast loading, Fluid–Structure Interaction, Sandwich panel, Honeycomb core, ABAQUS, CEL method, Energy absorption.

I. INTRODUCTION

The rising trend of accidental explosions, incidents in industries, terrorist actions, and military activities have resulted in a higher need for structures that are able to resist dynamic loads. The blast loading creates a very intense pressure wave over a short time period, causing immense damage to structural elements along with their deformation and possible failure of the conventional structure. In this regard, there is a need for developing effective protective structures that would be efficient in absorbing and dissipating the energy generated due to blast loadings.

Among all the different types of protection structure systems, the sandwich panel has received considerable attention due to its outstanding weight to stiffness ratio, energy absorbing capability, and structural effectiveness. A typical sandwich panel is made up of two stiff layers of face plates bonded together with a light core made up of honeycombs, foams, or corrugations. The face plates provide resistance to flexure or membrane actions while the core provides transverse shear resistance, restrains the face plates against buckling failure, and absorbs energy through gradual crushing. Because of these attributes, sandwich panels are widely applied in aerospace structures, ships, offshore structures, armored vehicles, and blast-resistant building structures.

Under blast loading, the behaviour of sandwich panels tends to become very nonlinear and transient. First, the shock wave impacts the outer face sheet, where it produces high levels of compressive stress and deformation. Then, the transmitted force travels through the core, impacting the inner face sheet, where it produces complicated deformation processes such as bending, stretching, and crushing. Sandwich panels can demonstrate different characteristics depending on certain criteria like the geometry of the core and properties of face sheets, among others. For this reason, knowing the effects produced by those criteria becomes very important in order to design blast-resistant sandwich panels.

Fluid–Structure Interaction (FSI) plays a key role in determining how a sandwich panel will respond to a blast load. Under practical blast loading conditions, the medium in which the structure is immersed, such as air or water, acts in conjunction with the structure and modifies the pattern of pressure distributions, wave reflections, and transmission mechanisms of energy within the structure. The presence of a medium can provide additional damping and inertial forces that will reduce the structural response but will extend the period of the load application as well as its magnitude. Nevertheless, traditional methods of predicting structural response in such cases ignore these aspects.

The progress made in modern computational mechanics as well as in finite elements allowed for a much more precise prediction of blast-induced responses of structures with the help of coupled fluid–structure analysis. The software package ABAQUS/Explicit offers a good way to model blast loading with the help of CEL method. Therefore, modern numerical simulations became an indispensable means of assessing structural performance under blast loading conditions and studying the influence of different design parameters on such response.

While there exist many investigations regarding the performance of sandwich panels under blast loads, relatively few investigations have been conducted on understanding the effect of fluid content on their performance. There is a lack of understanding regarding how fluid affects the deformation behavior, pressure reduction, and energy dissipation in sandwich panels. In this regard, the current study focuses on the effect of fluid content in honeycomb sandwich panels subjected to blast loading through Fluid Structure Interaction Analysis using ABAQUS/Explicit software. The aim of this analysis is to identify the optimum fluid fraction value to be used in blast mitigation.

II. AIM, OBJECTIVES AND SCOPE

The aim of this study is to numerically investigate the influence of varying fluid fractions within a honeycomb sandwich panel on its blast response using a Fluid–Structure Interaction (FSI) framework. The research seeks to identify the fluid configuration that provides the most effective blast mitigation by reducing structural deformation and improving energy absorption characteristics.

The objectives of this study are to investigate the blast response of honeycomb sandwich panels under varying fluid-filled conditions using a Fluid–Structure Interaction (FSI) framework and to evaluate the influence of fluid fraction on the structural behaviour of the panel.

The study seeks to compare the displacement response, stress distribution, and pressure attenuation characteristics for fluid fractions ranging from 0% to 100% and to identify the configuration that provides the most effective blast mitigation. Furthermore, the research aims to examine the energy absorption and dissipation mechanisms by analysing internal energy, plastic dissipation, and frictional dissipation responses, thereby providing a comprehensive understanding of the role of fluid–structure interaction in enhancing the blast resistance of sandwich structures.

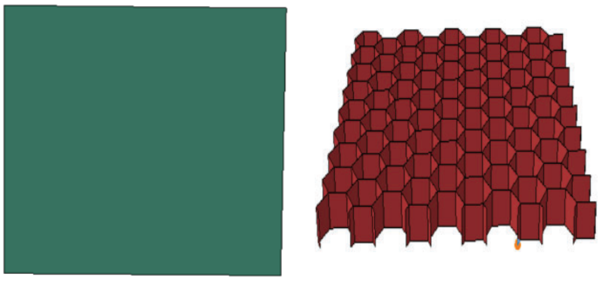
The current research explores the blast behavior of honeycomb sandwich structures having different fluid fractions with a Fluid Structure Interaction (FSI) analysis within ABAQUS/Explicit software. In this study, the effect of fluid fraction on pressure attenuation and deformation, stress distribution, and energy absorption by the honeycomb sandwich structure when it is subjected to a blast load is examined. In parametric studies, different fluid fractions varying between 0%-100% have been considered to see how they affect the blast mitigation capacity of the structure and improve its performance under blast loading. The energy dissipation capability of the sandwich structure in terms of internal, plastic, and frictional dissipation responses is also explored through this study to show how FSI can help increase blast resistance.

III. MODELLING AND METHODOLOGY

a) Geometric creation

The sandwich panel model consists of two metallic face sheets enclosing a hexagonal honeycomb core. The overall panel dimensions are 650 mm × 650 mm. The honeycomb core has a height of 50 mm and wall thickness of 0.76 mm. The geometric configuration was developed according to the validated numerical model reported by AlAhmed et al.

The honeycomb core was modelled using shell elements, while the face sheets were modelled using solid elements. Hexagonal cells were patterned uniformly throughout the panel area to ensure consistent load transfer.



(a) (b)

Fig 1 (a) Face plate (b) Honeycomb core

b) Material properties

AISI 4340 steel was used for both face sheets and honeycomb core due to its high strength and strain-rate sensitivity. The material behaviour was represented using the Johnson–Cook plasticity and damage model.

Elastic Properties:

- Young’s Modulus = 208 GPa
- Poisson’s Ratio = 0.3
- Density = 7830 kg/m³

Johnson–Cook Plasticity Parameters:

- A = 792 MPa
- B = 510 MPa
- n = 0.26
- C = 0.014
- m = 1.03

Johnson–Cook Damage Parameters:

- d1 = 0.05
- d2 = 3.44
- d3 = −2.12
- d4 = 0.002
- d5 = 0.61

The Johnson–Cook model captures strain hardening, strain-rate sensitivity, and thermal softening under high-speed loading conditions.

c) Assembly and Interaction

The assembled finite element model had three major parts: the top face sheet, bottom face sheet, and honeycomb core. The honeycomb core was placed between the two face sheets to create the overall structure of the sandwich panel. Proper alignment of all three elements was achieved to ensure smooth load transmission and realistic behavior of the assembly subjected to blast loading. To create bonding between the two face sheets and the honeycomb core, tie constraints were defined at the contact surfaces between these elements. These tie constraints did not allow any movement between the connected elements, ensuring load transmission across the faces of the connected elements through the entire process of blast loading.

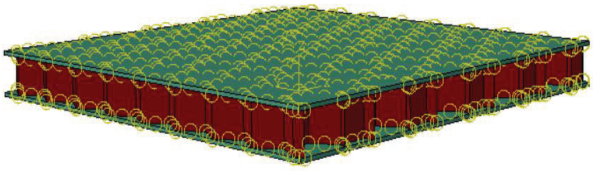


Fig 2 Assembled structure with tie interaction

d) Blast loading

Blast loading was performed through the CONWEP air-blast model incorporated in ABAQUS/Explicit. An explosive charge of 3 kg TNT equivalent was used, positioned at a standoff distance of 100 mm away from the center of the sandwich panel to model near-field explosion. The pressure-time curve was automatically created through the Modified Friedlander equation that describes the fast build-up of the blast pressure followed by its decay at an exponential rate. The blast loading was imposed on the top face sheet of the sandwich panel to perform the efficient simulation of wave propagation, stress-wave transfer, and deformation under blast loading.

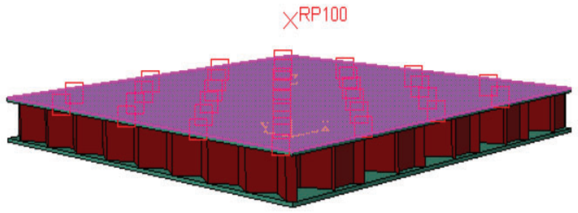
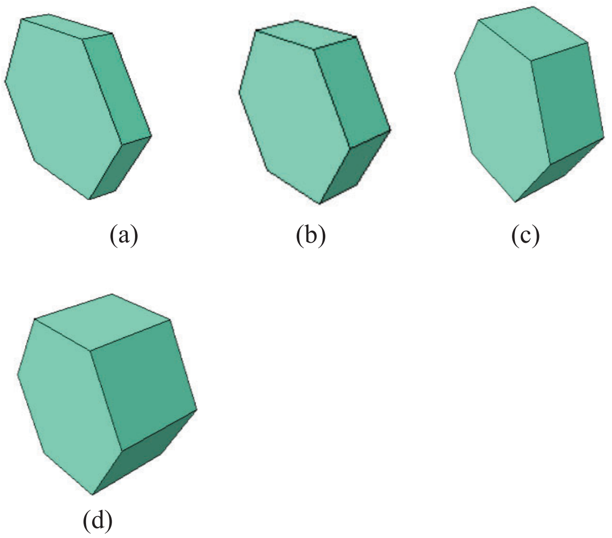


Fig 3 Blast loading surface with 100 mm stand-off distance

e) Fluid-Structure interaction

It allows for the simultaneous study of the propagation of the blast wave through the fluid medium and its effects on the subsequent structural behavior of the honeycomb sandwich panel, thus giving an accurate assessment of the pressure transfer and energy absorption processes due to a blast load. For the determination of the impact of fluid volume on blast protection, simulations were carried out with fluid percentages equal to 0%, 25%, 50%, 75%, and 100%. For assessing the performance of the structure under various fluid contents, a comparative evaluation of certain response parameters was made. These parameters include the maximum displacement value, stress distribution, internal energy (ALLIE), plastic dissipation energy (ALLPD), frictional dissipation energy (ALLFD), and pressure attenuation properties.



(a) (b) (c)

(d)

Fig 4 Fluid fractions (a) 25%, (b) 50%, (c) 75%, (d) 100%

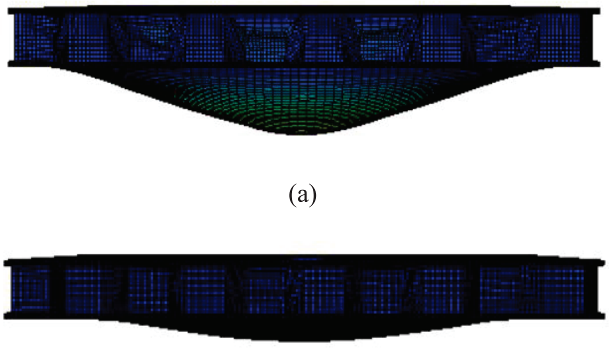
IV. RESULTS AND DISCUSSION

a) Comparison of Air-Blast and Fluid-Filled Conditions

With respect to the air-filled scenario (0% fluid volume), the shock wave was able to pass directly through to the sandwich panel structure without substantial loss, causing fast and intense accelerations, as well as severe deformation of the face sheet at the top of the panel. The transmitted shock wave induced high stress concentrations, causing progressive buckling and collapse of the cell walls located at the impact region. Thus, due to higher displacements, the air-filled specimen absorbed greater amounts of blast energy through structural deformations.

As fluids were introduced into the test set up, the coupling between the shock wave and the fluid medium caused changes in the nature of the loads applied on the panel. Part of the energy was absorbed by fluid flow processes and hydrodynamics prior to transferring load on to the structural elements. In this way, the fluids served as a secondary damping system, decreasing the magnitude of the transmitted pressure and delaying structural response. Consequently, lower deformations and better stress distributions were noted when using fluids in the experiment.

However, there were some non-linear effects with regards to the increase in fluid fraction. As the fluid fraction increased, it brought about an increase in hydrodynamic damping, which resulted in greater pressure attenuation and lesser peak deformations. But since the total fluid mass also increased, it increased the inertia of the whole panel leading to increased impulse transmission time and thereby influencing the manner of energy dissipation in the panel structure. Hence, blast mitigation using sandwich panels required balancing of hydrodynamic damping and structural flexibility in order to yield optimum results. All in all, one can clearly see from the comparison that Fluid-Structure Interaction plays a pivotal part in controlling the blast dynamics of honeycomb sandwich panels. Besides bringing about less structural deformation, fluid also helps dissipate energy more efficiently. These conclusions indicate the potential use of fluid-assisted sandwich panels in blast resistant structures.


(a)

(b)

Fig 5 Displacement contour (a) with Air core (b) with fully fluid filled core

b) Displacement behaviour

The displacement behavior of the sandwich panel was investigated to examine its deformation pattern and general performance when subjected to blast loads. The contours for the displacements indicated that the deformation pattern had a significant dome-shape, and the maximum out-of-plane displacement happened at the center of the face sheet on the top side of the panel, which was the area that the blast wave hit directly. Such deformations are expected in view of the pattern of pressures created by the blast loading, where the maximum value of the pressures occurs at the center of the panel and gradually reduces at the edges. Considering that the fully clamped conditions restrained any displacements from happening at the edges of the panel, deformations would be mostly confined to the central part of the panel leading to the occurrence of bending and localized deformations in the honeycomb core of the sandwich panel.

Deformation occurred due to the synergistic effect of bending of the face sheets, stretching of the membrane, and gradual crushing of the honeycomb core. Right after the arrival of the shock wave, the top face sheet started moving downwards quickly, resulting in the development of compressive stresses in the upper section of the core. As the load passed through the composite panel, thin walls of the honeycomb structure got bent, folded, and plastically deformed, thus dissipating a considerable amount of energy. Such a crushing phenomenon decreased the level of the load being transmitted to the bottom face sheet, thereby providing some blast resistance to the panel. It can be said that deformation of the bottom face sheet was less intense than that of the upper one since a certain part of the blast energy was dissipated by deformation of the core.

A significant impact of fluid fraction on displacement behavior has been established during the comparison of results obtained using the respective simulations. In the case of 0% fluid scenario, the peak displacement is maximal since the passage of the shock wave occurred directly through the air-filled zone without any significant reduction in its intensity. The absorption of more blast energy by the structure through structural deformation caused increased displacement of face sheets and crushing of the honeycomb core. When the fluid fraction was increased, the decrease in displacement was caused by FSI effects that became more pronounced with increasing fluid fraction. Hydrodynamic resistance provided by the fluid led to the reduction of the blast pressure and delayed acceleration of the structure.

Displacement plots also show that there was a gradual decline in deformation levels from the center of the structure towards its edges. This shows that the loads produced by the explosion were effectively redistributed from the honeycomb core and face sheets. The stiff nature of the core ensured that loads were effectively transferred without inducing excessive deformations. The decrease in displacement levels for the fluid-filled configuration confirms that the inclusion of fluids plays a key role in increasing the blast resistance and deformation of honeycomb sandwich panels under extreme loading conditions. Fluid-Structure Interaction plays a key role in the process by dissipating loads.

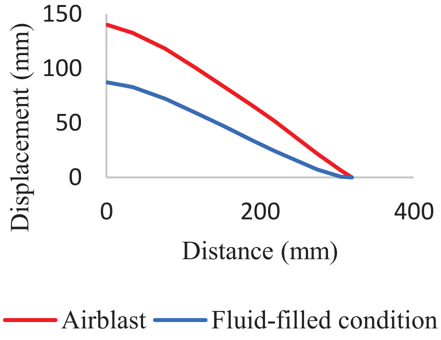


Fig 6 Displacement vs distance graph

c) Stress distribution

The stress pattern in the sandwich panel subjected to blast loading was greatly dependent on the interaction of the shock wave, face sheets, and honeycomb core. Upon explosion, the incident shock wave would immediately act on the top face sheet, resulting in high-stress levels being produced in the middle part of the sandwich structure. The blast loads were characterized by their extreme rapidity and high levels; therefore, the propagation of stress waves in the thickness of the sandwich structure led to a combination of compressive, tensile, bending, and shear stresses.

This was due to the fact that the top face sheet was subjected to the highest amount of stresses, since it was subjected to the direct impact of the explosion wave. Compression stresses arose in the panel surface due to the contact with the explosion wave, while bending tensile stresses occurred on the other side of the face sheet when the panel deformed. The location of maximum stresses in the central part of the panel coincided with the location of the greatest deformation and therefore was the critical point, where the initiation of damage could occur. Stresses arising in the panel passed to the honeycomb core from the top face sheet through their interfaces under the action of the blast wave pressure.

The honeycomb core acted as the main element for load redistribution within the composite structure. When subjected to blast loads, the thin walls of hexagon-shaped cells were put under compressive and shearing forces, thus causing buckling, wall folding, and plastic deformation. In the end, the aforementioned deformation processes redistributed the stress concentrations away from the impacted area into other parts of the honeycomb core. The core did not transfer the blast force directly to the bottom face sheet, but rather absorbed a significant amount of the force in the form of crushing. This process limited the stress concentration on the bottom parts of the sandwich and contributed to a more gradual failure process.

Stress levels were low in the bottom face sheet due to the fact that the energy of the blast had been partially absorbed by the deformation of the top face sheet and the core material. Nevertheless, tensile stresses developed in the bottom face sheet during the latter parts of loading due to global bending and rebounding. Tensile stresses are of great importance since they control cracking or failure under harsh blast loading conditions. The transition of stresses from the impact side to the support side shows the success of the sandwich structure in minimizing shock stresses.

Effects of Fluid–Structure Interaction (FSI) were further noticed from the stress response behavior of the panel as well. In case of an air-filled panel, there was direct transmission of the blast wave on the panel, hence higher peak stresses and concentration of stresses on the face sheets as well as honeycomb cores. However, with an increase in the fluid fraction in the panel, hydrodynamics played an effective role in weakening the pressure wave and hence decreased stress values on the structural elements. Fluid acted as a buffer layer that dissipated some energy from the blast wave before reaching the panel. This led to reduced peak stress values as well as stress concentration.

Conclusively, from the stress analysis, it is clear that the interaction between the face sheets, the honeycomb core, and the fluid medium surrounding them is extremely important in controlling the structural behavior when subjected to blast loads. The stresses within the structure can be reduced by the honeycomb core through progressive failure, whereas the fluid-structure interaction results in the reduction of the magnitude of the loading.

d) Energy absorption and dissipation mechanisms

The performance of the honeycomb sandwich panel regarding its energy absorption was assessed using the total internal energy (ALLIE), plastic dissipation energy (ALLPD), and frictional dissipation energy (ALLFD). As a result of blast loading, there was an instantaneous increase in kinetic energy caused by the impulse pressure created from the explosion. During the deformation process, the kinetic energy would be converted to internal energy through elastic and plastic deformation of both the face sheets and honeycomb core. An increased value of ALLIE denotes the amount of energy absorbed by the structure after blast impact, while ALLPD refers to the amount of energy that has been dissipated through irreversible plastic deformation.

The effects of various fluid fractions were compared, which clearly showed that Fluid Structure Interaction (FSI) played a vital role in altering the energy dissipation properties of the panel. In case of the air-filled arrangement, more of the blast energy was transferred into the structure itself leading to more energy dissipation and deformation of the panel. With increasing fluid fractions, some of the blast energy was absorbed by the hydrodynamic effect, thus leading to reduced structural loadings. Even though frictional dissipation energy (ALLFD) did not account for much of the total dissipated energy when compared to ALLIE and ALLPD, the synergy of plastic deformation and energy dissipation due to hydrodynamics enhanced the blast protection properties of the sandwich panel.

Moreover, it is important to note that the differences in the energy components help in identifying the major factors for blast mitigation in the sandwich structure. The core layer helped in absorbing a large part of the transmitted energy in the form of cell wall buckling, folding, and crushing. In addition, the core layer helped in controlling the deformation process and hence preventing catastrophic structural failure due to blast loading. It is interesting to note that with increase in fluid volume, there is decrease in internal and plastic dissipation energy. This implies that the fluid around the structure helps in dampening the impact of blast load before the structure faces the load.

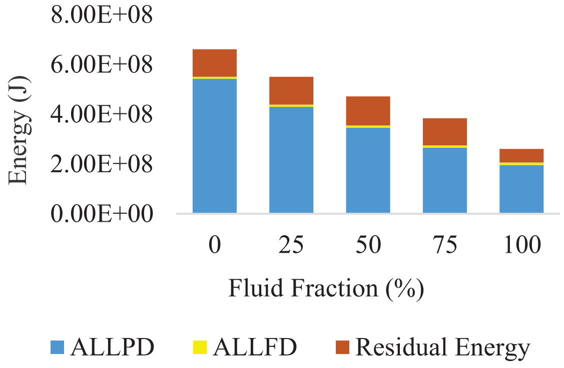


Fig Energy vs fluid fraction

e) Optimum fluid fraction assessment

All configurations filled with fluid were compared with one another in terms of their effectiveness as far as mitigating blast is concerned. It was discovered through the comparative study of all those configurations that the response of the structure was highly dependent on the fluid fraction of the system. The more fluid there was inside the structure, the less was the pressure generated by the blast. Hydrodynamic damping played a significant role in diminishing the transmission of blast pressure as well as the displacement caused by the effect of blast waves. But the efficiency of blast mitigation was not directly proportional to the fluid fraction, which proved that there was an optimum fraction of fluid.

Intermediate fluid fractions performed best due to the balanced effects of pressure mitigation, energy dissipation, and mechanical stability of the structures. With low fluid fractions, the effect of the fluid on reducing the blast wave transmission was too weak, which led to relatively high deformation and concentration of stress in the structures. On the other hand, fluid-filled systems increased the total mass of fluid and thus the inertia of the structure, which resulted in a longer period for the transmission of the impulse and lower deformation levels. This affected the dynamic response of the panels and the effectiveness of the energy dissipation processes. Thus, the optimal fluid fraction refers to the case where the maximum possible decrease in the deformation and stress concentration was achieved while maintaining efficient energy dissipation through the fluid-structural interaction processes.

The aforementioned behavior suggests that the process of blast protection for fluid-filled sandwich structures involves two factors simultaneously, namely energy absorption due to the presence of a sandwich structure, and pressure attenuation because of the presence of the surrounding fluid. The effect of the surrounding fluid is such that besides decreasing the pressure value on impact, it changes the way stress/strain field develops in the structure itself. As a consequence, the loads are evenly distributed between face sheets and core, which means that there is no concentrated area of damage. It becomes clear that proper fluid content can improve the blast-protective properties of sandwich structures greatly. Thus, it may be concluded that a proper approach to designing blast-resistant structures consists in optimizing fluid fraction.

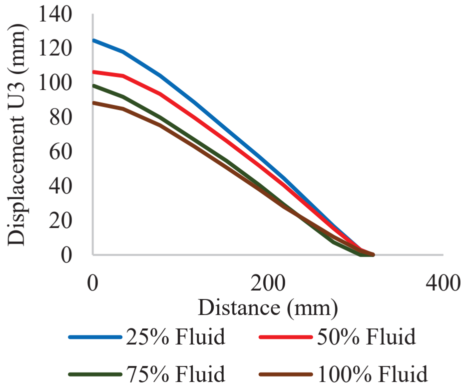


Fig Displacement vs distance graph of all cases

V. CONCLUSION

This current research has numerically analysed the behaviour of honeycomb sandwich plates under blast loading when filled with various amounts of fluids based on Fluid Structure Interaction (FSI) in ABAQUS/Explicit. The finite element model built for the numerical analysis has been able to capture the deformation response, stresses induced in the sandwich plates and the energy dissipated due to blast loading. It was observed from the numerical results that the fluid has a very significant effect on the deformation and stresses in the honeycomb plate, whereby the blast wave gets reduced due to damping by fluid and the deformation in the plate is minimal. The energy dissipation analysis showed that plastic dissipation plays a major role in absorbing the blast energy while frictional dissipation takes care of the small fraction of energy dissipation in the plate. It was revealed that the energy dissipation in such type of sandwich panels under blast loading is accomplished due to progressive buckling, folding, and crushing of the cell walls, which result in reduction in the load transmitted to the lower face sheet and delay of the structure failure process. In addition, the addition of the fluid to the honeycomb structure helped in improving the energy dissipation process by changing the nature of the pressure wave propagation and stress concentrations in the components of the structure. Such conclusions reveal the applicability of honeycomb fluid-filled sandwich panels as efficient and lightweight protection systems for various types of structures exposed to high-energy dynamic loading. The proposed simulation model can be applied to future investigations in this field in order to optimize the design of such structures, considering the use of alternative core shapes and materials. Fully fluid filled condition is obtained as fully fluid-filled condition.

VI. ACKNOWLEDGMENT

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