SIMULATION OF RAPID STRUCTURAL FAILURE DUE TO BLAST LOADS FROM CONVENTIONAL WEAPONS (CONWEP)

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THEME

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SUMMARY

Protecting buildings, bridges, and vehicles is a critical component of military and homeland security. The explosive force caused by conventional weapons can cause significant damage to nearby structures and vehicles as well as possible physical harm to the people within the confines or proximity of such structures. Protecting individuals as well as the structures involves the use of specialized materials, sandwich designs, and reinforced coatings. The widely used commercial finite-element software Abaqus/Explicit has been recently enhanced to enable engineers to simulate the damage due to such blast loads and to design structures that can withstand the resulting forces. In this paper, simulation of rapid dynamics of a honeycomb-core sandwich structure under blast loads from conventional weapons is presented. Deformations due to different explosive-charge amounts from a fixed distance are simulated. Results from simulations are compared to measurements from experiments. The response of the sandwich structure is also compared to that of an equivalent solid plate (by weight). Comparisons demonstrate that the enhanced explicit solver in Abaqus can be reliably used to simulate structural damage due to such explosions.

BLAST LOADING DUE TO CONVENTIONAL WEAPONS (CONWEP)

1: Introduction

Explosions caused by conventional weapons can cause severe damage to nearby structures such as buildings, pipelines, bridges, vehicles etc., leading to significant loss of life and property. Engineers from military, automobile industry, oil and gas industry, nuclear industry, and several other organisations need to develop designs for blast mitigation. These designs must be validated either experimentally or using simulations. Experiments are expensive as they involve damage to the models and require rapid data measurement systems. Information from previous experiments is often not publicly available, because such tests are conducted by defense organisations or affiliated agencies, and remain as classified information. Hence, simulations play an important role in validating structural designs against blast loads. Most of the simulations have been conducted using empirical models for blast phenomena, since detailed computational fluid dynamics (CFD) simulations become computationally expensive. One of the most commonly used models is the CONWEP model, initially developed by Kingery and Bulmash (1984). Simulations have been conducted using the Abaqus/Explicit software (Dassault Systemes Simulia Corp. 2010), where the blast loads were externally defined (Dharmasena, et al. 2008). Recently, this feature has been implemented as a built-in functionality in Abaqus/Explicit software (in version 6.10) making it convenient to subject models to diverse blast loads.

Sandwich structures have been shown to be effective in withstanding blast loads from explosions by researchers in the last decade [(Xue and Hutchinson 2003), (Xue and Hutchinson 2004), (Radford, et al. 2006), (Vaziri, Xue and Hutchinson 2007)]. In the current paper, the authors present simulation of a recently-conducted experiment by Dharmasena, et al. (2008) on all-metal square-honeycomb structure subjected to blast load, using the newly implemented CONWEP model in Abaqus/Explicit. The paper first presents an overview of blast phenomena where some details of the CONWEP models are mentioned. Thereafter, previous findings on sandwich structures are described. Next, the details of the test cases and their simulations are presented. Deformations due to different explosive-charge amounts from a fixed distance are simulated. Results from these simulations are compared to the measurements from experiments. The response of the sandwich structure is also compared to that of an equivalent solid plate (by weight). Comparisons demonstrate that the enhanced explicit solver in Abaqus can be reliably used to simulate structural damage due to such explosions.

2: Conventional Weapons and the blast phenomena

Nuclear weapons, chemical weapons, and biological weapons are notorious for causing large scale mass destruction. Those weapons which do not cause such large scale mass destruction and yet are capable of causing significant damage to life and property are generically referred to as ***conventional weapons***. These weapons typically include land mines, non-nuclear bombs, shells, rockets, missiles etc. The threat from such weapons is measured by the mass of the explosive, or the *charge mass*; and the distance of the explosion from the vulnerable structure or the *standoff distance*. The charge mass used in conventional weapons is typically measured in kilograms of TNT. For comparison, nuclear weapons release energy equivalent to that released by millions of conventional explosives and their charge mass is generally referred in kilotons of TNT. For example, the conventional explosives detonated in the basement of the World Trade Center in New York City, USA on February 26th of 1993, had a charge mass of 816.5kg TNT (Ngo, et al. 2007), whereas the nuclear bomb deployed in the city of Nagasaki, Japan on August 9th of 1945 had an explosive power approximately equivalent to 21 kilotons of TNT (Gosling and Fehner 2000).

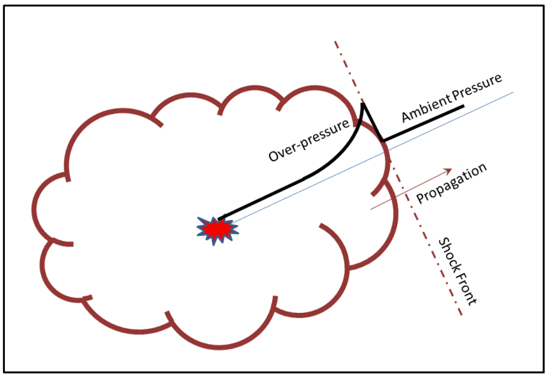

Figure 1: A schematic of the pressure distribution across a blast wave.

Detonation of an explosive involves chemical reactions which causes rapid heating and expansion of the detonated products. This rapid expansion causes abrupt compression of the surrounding medium, leading to a strong shock wave, commonly known as a *blast wave*, which propagates away from the source with high velocity. The state of the medium, described by its pressure, density, temperature, and velocity are discontinuous across the shock front. The states before and after the shock are related by the conservation of mass, momentum, and energy, which are collectively expressed as the well-known Rankine-Hugoniot jump condition. The blast waves are typically supersonic (moving with a speed faster than the fastest-speed of propagation of any perturbation in the medium). Hence the medium remains unperturbed until the advent of the shock front, with the pressure just ahead of the shock (away from the source) remaining close to ambient pressure. The pressure just behind the shock, often referred to as the *over pressure*, propels the shock away from the source, as shown qualitatively in Figure 1.

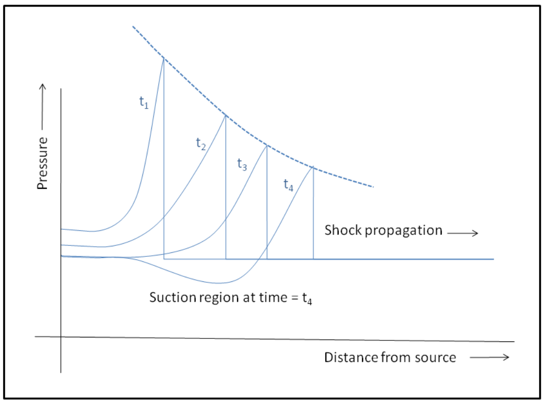

Figure 2: Pressure distribution at different time levels ($t_1 < t_2 < t_3 < t_4$).

As the shock propagates away from the source, this over pressure reduces, causing the pressure of a region, behind the shock, to drop below ambient pressure, which causes transport of debris far away from the explosion source. The pressure distribution at different time levels is qualitatively shown in Figure 2. A typical time history of the pressure inflicted by a blast wave at a fixed distance from the source is shown in Figure 3.

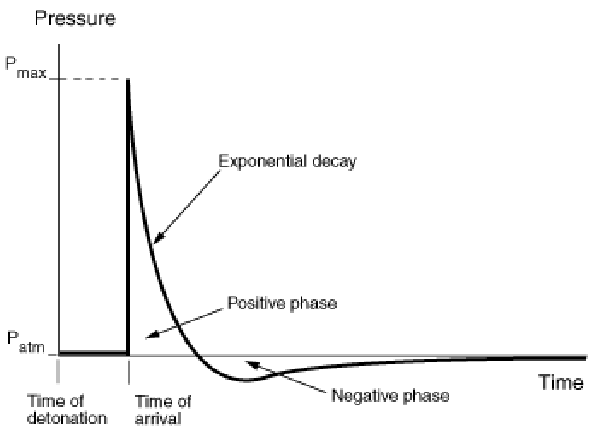

Figure 3: Time history of pressure due to a blast wave at a given location.

This qualitative model has been known and developed by several researchers directly or indirectly working for defense organisations. Much of their work has remained classified information and is not available for public access. Earliest among the more publicly known information are the researches by Taylor, G. I. (1950), Friedrichs, K. O. (1948), Brode, H. L. (1955), and Baker, W. E. (1973). Later the model developed by Kingery and Bulmash (1984), more commonly known as the CONWEP model, has been widely used for free explosions in air. It has previously been implemented in the

DYNA2D/DYNA3D software (Randers-Pehrson and Bannister 1997) and in the **ConWep** software (Protective Design Center, U. S. Army Corps of Engineers 2010). The CONWEP model can be briefly described by expressing the free-field pressure–time response by a modified Friedlander equation (Dharmasena, et al. 2008):

$$p(t) = (p_{max} - p_{atm}) \left[1 - \frac{t - t_a}{t_d}\right] e^{-\frac{a(t-t_a)}{t_d}} \tag{1.1}$$

$$I = \int_{t_a}^{t_a+t_d} p(t)dt \tag{1.2}$$

where p_{atm} is the atmospheric pressure, $(p_{max} - p_{atm})$ is the over-pressure, t_a is the time of arrival of the shock front, t_d is the duration of the positive phase, a is the decay constant and I is the impulse of the blast at the given location. The time of arrival, the duration of the positive phase and the impulse of the blast depend on the distance of the location from the source, the charge mass and other parameters defined in the CONWEP model. The decay constant is iteratively calculated from the impulse, over-pressure, and duration of the positive phase, using Eqn. 1.2.

When an incident blast wave impinges on a surface, it creates a secondary wave that reflects from the surface, often called the *reflected wave*. The pressure felt by the surface is the combined effect of the incident wave and the reflected wave. It can be interpreted as the reaction force (applied by the medium on the surface) per unit area, due to the rate of change of momentum of the particles of the medium. To calculate the pressure felt by the surface, the pressure from the incident and the reflected waves are calculated separately. The combined pressure $p(t)$, depends on the angle at which the shock impinges on the surface. If the angle of incidence (say θ) is the angle between the outward facing normal and the ray that joins the point on the surface to the source, then the pressure felt by the surface is related to the incident pressure $p_i(t)$ and the reflected pressure $p_r(t)$ as follows:

For $\cos\theta \geq 0$

$$p(t) = p_i(t)[1 + \cos\theta - 2\cos^2\theta] + p_r(t)\cos^2\theta$$

For $\cos\theta < 0$ (1.3)

$$p(t) = p_i(t)$$

This relation has been developed by curve fitting pressure measurements from experiments. A detailed study on blast wave reflection can be found in the book by Smith and Hetherington (2003). A detailed comparison of the CONWEP model, using the **ConWep** software (Protective Design Center, U. S. Army Corps of Engineers 2010), and other similar models and a vast collection of test data was conducted by Bogosian, Ferrito and Shi (2002), where it was inferred that the CONWEP model best represented the test data in an overall sense. The CONWEP model is based on data from free-air explosions; hence it does not include effects of reflections due to confinement and shadow effects from one body on another (Remennikov and Rose 2005). A more accurate modeling of blasts using computational fluid dynamic (CFD) analysis with fluid-structure interaction to simulate the detonation of a high-energy explosive (HMX) confined in a thick-walled solid cylinder was conducted by Deiterding, et al. (2006). A recent research (Miller, et al. 2010) comparing the CONWEP model to a coupled Eulerian-Lagrangian (CEL) analysis, and a fully Eulerian analysis using the CTH software (McGlaun, Thompson and Elrick 1990), demonstrates effects of blast-structure interactions at close vicinity to explosion source.

3: Sandwich Structure

Over the last decade, several studies have been conducted to develop structures that can withstand blast loads from conventional explosives. Sandwich structures, where a core region is covered by top and bottom plates, are considered effective for blast mitigation among other techniques like use of high-strength materials, specialized coatings etc. A preliminary assessment was done by Xue and Hutchinson (2003), where they found that for the same material and structural mass, sandwich structures could sustain substantially larger uniform impulses than a solid plate. They used clamped circular geometry. The sandwich structure had a tetragonal truss core, and was modeled by a continuum model that was derived from a previous research (Deshpande and Fleck 2000). In a subsequent study (Xue and Hutchinson 2004), three classes of all metal (stainless steel #304) sandwich structures, viz., truss, honeycomb and folded cores, were compared. The simulations were conducted using Abaqus/Explicit software, with finite element mesh for plates and cores, comprising of eight noded linear brick elements with reduced integration. The loading was simulated by displacing a punch on the top plate. Quasi-static behavior was also studied using Abaqus/Standard software. They found that square honeycomb and folded plate cores outperformed truss cores, but all three types of sandwich plates were capable of sustaining larger blasts than the solid plate of equal mass. A study for comparing sandwich structures with metallic foam, using metallic foam projectile was conducted by Radford, et al. (2006). A comparison of square metal honeycomb core versus a folded metal core, with several material properties and failure models has been studied by Vaziri, Xue and Hutchinson (2007) using Abaqus/Explicit, using spatially uniform and temporally exponentially-decaying pressure loads that depend on the impulse and duration of the load.

Recently, Dharmasena, et al. (2008) conducted experiments on an all-metal square-honeycomb sandwich structure and the experimental results were compared to finite element simulations using Abaqus/Explicit software. The loading was approximated by a pressure distribution exponentially decaying with the projected-distance from source, and varying in time with parameters that were obtained by fitting the results from calculations made with **ConWep** software (Protective Design Center, U. S. Army Corps of Engineers 2010). Those experiments (Dharmasena, et al. 2008), are re-simulated in this paper, using the in-built CONWEP model, instead of the approximate loading. The specific strain-hardening model described in the paper was replaced by the conventional Johnson-Cook plasticity model (Johnson and Cook 1983). Other details of the model and simulation are described in the next section.

4: Simulation and Results

Simulations described in this paper are chosen from the experiments conducted by Dharmasena, et al. (2008) to demonstrate the usage of CONWEP blast loading in Abaqus/Explicit software. In the first set of experiments, conventional explosives were detonated from a fixed distance (100 mm) from a solid metal plate which was held fixed by clamped ends. In the next set of experiments, the explosives were detonated over an all-metal sandwich structure with a square honeycomb core. For both sets, explosives of charge mass of 1, 2 and 3 kg TNT were detonated. Both, the solid plate and the entire sandwich structure (including the top and bottom plates and honeycomb core), were made of a high ductility stainless steel alloy (AL-6XN) comprised of 49% Fe, 24% Ni, 21% Cr, and 6% Mo by weight. This alloy was modeled as rate-dependent plastic material, with Johnson-Cook model for strain hardening (Johnson and Cook 1983) and Johnson-Cook model for rate dependency, as explained in Eqns. 1.4-5.

$$\sigma_Y = \left[A + B\left(\varepsilon_e^{pl}\right)^n\right]\left[1 + C\ln\left(\frac{\dot{\varepsilon}_e^{pl}}{\dot{\varepsilon}_0}\right)\right](1-\alpha^m) \tag{1.4}$$

$$\alpha = \frac{T - T_{tr}}{T_M - T_{tr}} \tag{1.5}$$

where ε_e^{pl} is the equivalent plastic strain, $\dot{\varepsilon}_e^{pl}$ is the equivalent plastic strain rate, T_{tr} is the transition temperature, and T_M is the melting temperature. A ton-millimetre-second-Kelvin unit system was chosen for all simulations. The unit of force in this system remain the same as that in SI system (Newton) while the unit of pressure in this system becomes mega Pascal (MPa). The mechanical properties for the AL-6XN were obtained from (Nahshon, et al. 2007) *viz.*: Young's modulus of 1.61×10^5 MPa, Poisson's ratio of 0.35, density of 7.89×10^{-9} metric-ton/mm^3, coefficient of expansion of 452×10^6 (N×mm)/(metric-ton×K). In the Johnson-Cook model (as described in Eqns 1.4-5), the values of the constants were: A = 400 MPa, B = 1500 MPa, C = 0.045, n = 0.4, m = 1.2, and $\dot{\varepsilon}_0 = 0.001\ s^{-1}$, T_{tr} = 293 K, and T_M = 1800 K. For both the sets, solid-plate and the sandwich structure, symmetry of deformation was assumed, due to the square geometry, homogenous and isotropic material and identical clamped boundary conditions on all edges. Taking advantage of the symmetry, only one quarter of the geometry (a square of 305 mm × 305 mm) was modeled, applying clamped boundary conditions at the external faces and symmetry boundary conditions (out-of-plane displacements and in-plane rotations not permitted) for the internal faces. The explosive was located at a fixed stand-off distance of 100 mm from the center of the plate (0, 0,100). The sandwich structure had a thickness of 51 mm. The thickness of the solid plate was chosen to be 12.7 mm, to make it equivalent to the sandwich structure in terms of material mass as described in (Dharmasena, et al. 2008). In the following subsections, model-features and results of the two test cases are described in detail.

4.1 Solid Plate

Two models were developed for the experiments on the solid plate. The first model was comprised of 31×31 four-noded bi-linear shell elements with reduced integration (S4R) in the square quadrant of side of 305 mm. The shell elements had nine integration points through the thickness. The second model was comprised of 31×31×5 continuum-3D eight-noded solid elements with reduced integration (C3D8R). Enhanced hourglass control was used for all elements in both models with default settings. The solutions were computed for 1.5 milliseconds, a time level, where the mid-surface deformation of the center of the plate reached a steady value. Consistent deformation behavior was found across the two models which compared well with the experiments as discussed in the next section.

4.2 Sandwich Structure

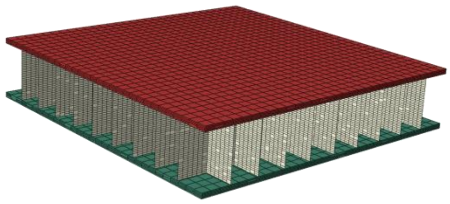

Figure 4: The sandwich structure. Colours indicate regions of the mesh.

The sandwich structure, as shown in Figure 4, comprised of a 5 mm thick top plate (in red, facing the explosive), a 51 mm high square-honeycomb core and a 5mm thick bottom plate (in green), leading to a total thickness of 61 mm. The top and bottom plates were discretized using 31×31×5 continuum-3D eight-noded solid elements with reduced integration (C3D8R). The honeycomb core comprised of 9 vertically aligned (along y axis) and 9 horizontally aligned (along x axis) webs of 0.76 mm thickness, each discretized using 30 four-noded bi-linear shell elements with reduced integration (S4R), along the height of the core with five integration points across their thickness.

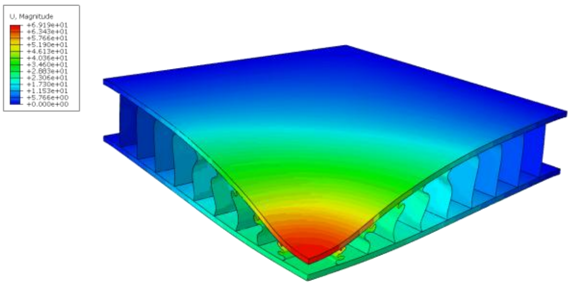

Figure 5: Deformation of the sandwich structure under 1kg TNT blast.

The top edges of the honeycomb core webs were tied (no relative displacement) to the bottom surface of the top plate, and similarly the bottom edges of the webs were tied to the top surface of the bottom plate. These tie constraints were an approximate representation of the brazing technique used to bond between the webs and the plates in the sandwich structure used in the experiments (Dharmasena, et al. 2008). Automatic detection of contact between all surfaces was employed during the course of the computation (general contact). The simulations capture large deformations with buckling and significant folding of the honeycomb webs, as shown in Figure 5, as reported in (Dharmasena, et al. 2008). A better view of the folding can be seen in Figure 6.

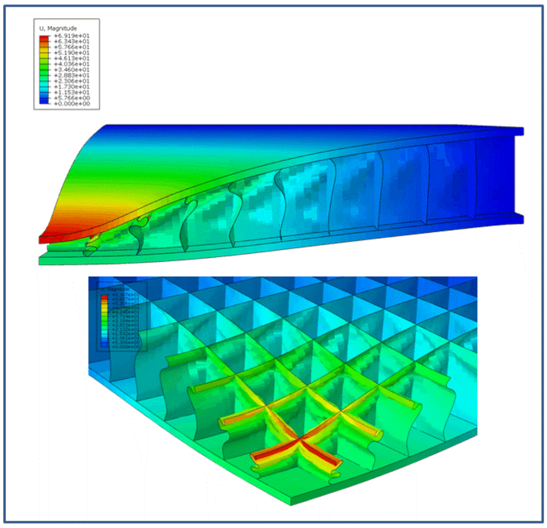

Figure 6: Details of deformation of the core under 1kg TNT blast, as seen from side (top) and as seen from top without the top plate (bottom).

5: Comparisons and Conclusions

The results obtained from simulations employing the built-in CONWEP model in Abaqus/Explicit compare well with measurements from experiments (Dharmasena, et al. 2008), as shown in Figure 7. The displacements of the solid plate center from simulations using shell elements and solid elements are almost identical. For the solid plate (mid-plane) and the sandwich structure (top and bottom plates), the plate center displacements from simulations are close to that measured from experiments. Less deformation of the bottom plate of the sandwich structure than that of the solid plate of equal structural mass indicates the advantage of the sandwich structure.

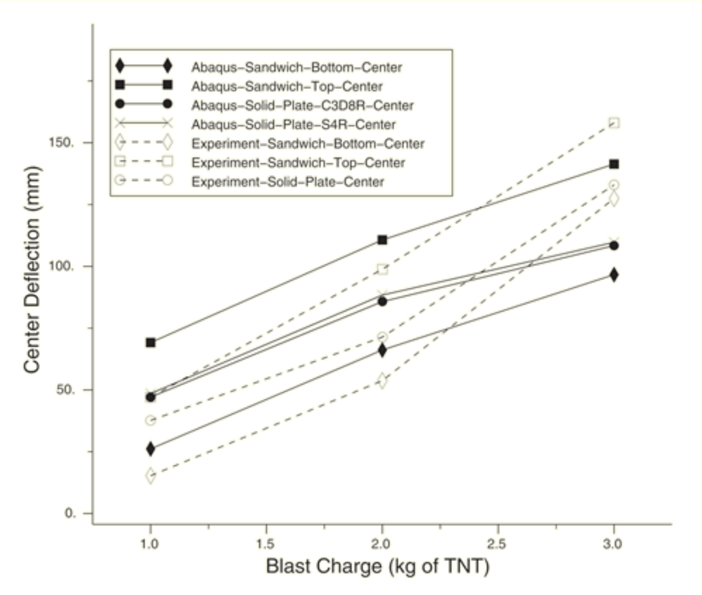

Figure 7: Comparison of center deflection between Abaqus/Explicit and experimental results for different blast charges.

Center displacements measured from experiments are larger than those from simulations for the 3kg TNT blast case for both solid plate and sandwich structure. Similar differences between experiments and computations (with approximate loads) are reported in (Dharmasena, et al. 2008) which were attributed to either imperfect clamping or weakening of the core (due to debonding of the webs from the plates), in the experiment at high blast charge. Further investigation is required to model such high intensity blasts

Overall, the simulations compare well with the experiments, considering that such tests involve complexities in experimental set-up and also simulations are known to be sensitive to choice of material models (Xue and Hutchinson 2004). It is evident that the built-in CONWEP model provides an effective and convenient functionality to reliably simulate structural deformations and damage under effects of blasts from conventional weapons.

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