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GASEOUS EXPLOSIONS AND THEIR GROUND EFECTS

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The effects of an explosion on underground structures are of increasing importance to the weapon designer interested in achieving a desired level of lethality [1,2]. This in turn requires an understanding of the pressure waves generated within the ground by an explosive charge either air-burst or buried, and the way they subsequently interact with buried structures. The size of the charge and its coupling efficiency with the ground are additional parameters of interest. A distributed charge has a greater potential to cause increased levels of damage to a structure, because of its ability to load more of a structure for a longer time. This paper presents some recent numerical modelling studies concerning a natural gas explosion and the loading generated on a buried gas main. The insights gained into the potential effectiveness of a distributed energy source and the numerical modelling challenges in its simulation are presented and discussed.

INTRODUCTION

The effects of an explosion on underground structures are of increasing importance to the weapon designer interested in achieving a desired level of lethality [1,2]. This in turn requires an understanding of the pressure waves generated within the ground by an explosive charge either air-burst or buried, and the way they subsequently interact with buried structures. The size of the charge and its coupling efficiency with the ground are additional parameters of interest. A distributed charge has a greater potential to cause increased levels of damage to a structure, because of its ability to load more of a structure for a longer time.

In December 1999 a natural gas explosion occurred in the under-floor space of a residential house in Larkhall, near Glasgow, in the UK, completely demolishing it and causing significant damage to the surrounding buildings.

A 272mm diameter 6.5mm thick ductile iron natural gas (methane) main, laid in approximately 1974, runs through the front gardens of the neighbouring houses and parallel to the roadway. This main operates in the medium pressure range (7.5×10^{-3}MPa to 0.2MPa). The post explosion investigation of this medium pressure main identified two visible holes in the pipe in the section of the main that ran through the garden of the site of the explosion. The holes in the pipe occurred in regions of graphitic corrosion.

One possible explanation was that the resulting pressure wave from the explosion in the under-floor space on impact with the medium pressure gas main dislodged the pieces of graphitic corrosion, identified by the post explosion investigation of the pipe. The numerical modelling study described in this paper addresses the credibility of this scenario and develops a modelling methodology which can also be applied to the more general study of buried structures subjected to blast and shock waves.

Using the energy equivalence between a methane-air mixture and TNT the energy released in the explosion was the equivalent of 100kg of TNT.

MODELLING STRATEGY

As the explosion event and its loading on the pipe are characterised by significant material deformation and motion the house, surrounding ground containing the gas main and the gaseous explosion source in the under floor void, referred to here as the explosion scenario, were represented using the QinetiQ developed Eulerian Hydrocode GRIM3D.

The structural response of the pipe, however, is characterised by mechanical stressing, deformation and failure. This is more appropriately represented using a Lagrangian method and DYNA3D was therefore selected. The input loads on the pipe in the DYNA3D simulation were obtained from the dynamic pressure loading histories around the pipe calculated in the GRIM3D simulation. In this way the most appropriate numerical methods were applied to the different aspects of the problem.

The geometrical details of the house, pipe and intervening ground were based on the information from various plans and reports of the structure and the properties of the materials used in its construction. In particular the under-floor space was characterised by a 50mm thick concrete solum. Our standard model for a wet clay based soil was used to represent the ground conditions. The house, methane-air mixture and surrounding terrain, including the gas main were represented on a 5.89 million-cell (250 x 203 x 116) numerical constant cell size mesh (15cm), representing a physical domain 37.5m by 30.45m by 17.4m centred on the house. The initial mesh is shown in Figure 1. The problem time was 140ms.

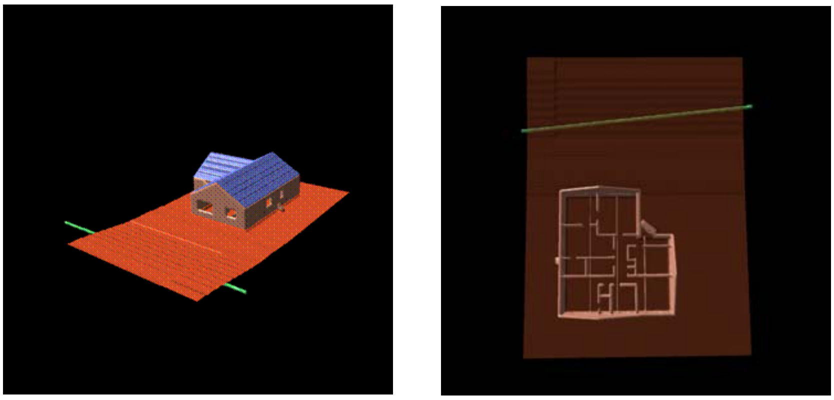

Figure 1: Initial explosion scenario and internal wall layout (right)

Energy Release

Unlike a condensed explosive, where the energy release is governed by the detonation wave, a gaseous explosion is governed by the flame speed, whose velocity is variable and a strong function of the chemical composition of the gas-air mixture and its physical surroundings, i.e. confinement.

Depending on the initial conditions within the mixture and the environment of the under floor void the burning rate of the gas can vary by several orders of magnitude. Combustion in flammable gaseous mixtures is a complex problem. Not all gaseous mixtures are flammable. In the case of methane-air the flammability limits are highly clustered about the stoichiometric mixture and this is the condition considered in this study. A stoichiometric reaction is a unique reaction in which all of the reactants are consumed.

The rate of energy release is governed by the flame speed that results on ignition of the mixture. The slowest flame speeds are associated with laminar flames and in a methane-air mixture these speeds are of order $3.5m.s^{-1}$. The burning velocity under these circumstances is about $40cm.s^{-1}$, ($0.4m.s^{-1}$), for a stoichiometric mixture considered here. In complex geometries relevant to real life scenarios, however, turbulence is the dominant mechanism in defining the flame speed. The waves propagating away from a laminar flame can reflect from obstacles and boundaries and hence interact with the flame. These interactions, together with natural instability processes, lead to the formation of a turbulent accelerating flame front. Turbulent flame speeds can be of the order of hundreds of metres per second and under the correct conditions can ultimately transition into a detonation wave, which in the case of methane-air travels with a velocity of $1800m.s^{-1}$.

Bakke [3] using the combustion code EXSIM, studied this explosion and produced maps of the progress of the flame through the under-floor space and in the rooms above concluded that the explosion was caused by an accelerating flame front.

The Bakke's results were used to estimate the position of the flame front with time and hence the volume of the gas consumed by the flame against time. The ratio of this volume to the total volume of gas was then multiplied by the specific combustion energy to provide the specific energy release as a function of time, using the simple energy release algorithm [4,5] in GRIM previously shown to be capable of reproducing the physics of combustion. The specific energy release with time profile derived in this way is shown in figure 2 together with the assumption of a constant velocity flame travelling at 100m.s^{-1} for comparison.

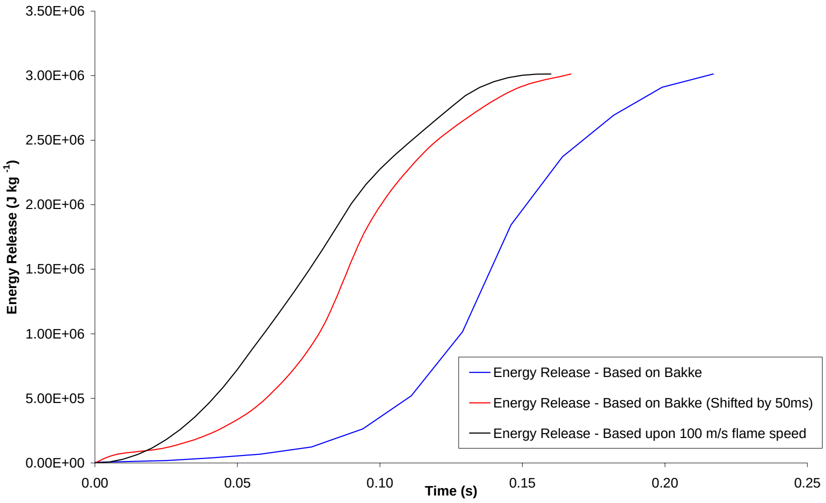

Figure 2 – Energy Release Time Profile

Figure 2 shows that the energy release occurs over about 0.2s. It also shows that the amount of energy released over the first 50ms is very small. To reduce the overall simulation time the release profile was therefore shifted by 50ms as shown by the dotted curve in the figure. The figure also shows that a constant velocity flame speed of 100m.s^{-1} is a good approximation to the energy release.

Gas Main Model

The two areas of corrosion, observed in the pipe post explosion as holes, were included in its description in the DYNA simulation and were approximately 4.25m apart. The centre of the pipe at the first defect was located at a depth of 2.4m at a distance of 10.7m from the explosion source. The total length of the pipe included in the simulation was 32m. An Armstrong-Zerilli description of the strength of the Spheroidal Graphite or Ductile Iron (SGI) medium pressure gas main was specified.

In the absence of the material strength tests of the corrosion product we used the research study completed by Sear [6] in 1968 on the bursting pressures of corroded pipes. The data presented in the reference whilst limited, allowed us to estimate the failure criteria of corroded pipes but not corrosion product. At the burst pressures specified by Sear [6] the average stress in the pipe would have been 24MPa, which provides an upper limit on the likely failure stress of corroded pipes. Since the dimensions of the corroded region were not available and the iron carbonate corrosion product was rather weaker, the failure stress of the corroded pipe could have been as little as a quarter of this upper value, i.e. potentially down to 6MPa. In the simulation the pipe was therefore modelled with the same material description throughout, however in the regions of the two defects a failure criterion was specified as a maximum stress.

The simulation assumed that the corroded region reduced in direct proportion to the depth into the pipe. The gas main response simulation was repeated with the corroded pipe failure stress criterion specified as 6MPa and 12MPa.

EXPLOSION SCENARIO

As the initial blast wave propagates through the house and the under-floor void it is reflected and refracted by the internal walls and structures, such as the solum and other parts of the foundations. A series of multiple reflections therefore develops within the house and its foundations, which interact as they propagate into the soil. The resulting pressure wave that is then created propagates through the surrounding soil and loads the gas main. The load on the gas main is therefore temporally and spatially complex.

The gas above floor level effectively vents vertically through the roof and sideways through the walls generating shock waves in the air. Very little of the energy contained in these shock waves, as they propagate away from the house is radiated into the ground to load the gas main.

The increasing energy released as the explosion progresses, coupled with the reflection of waves inside the under-floor void and from the foundations leads to further compressive waves that propagate out into the soil. In addition the strong reflections within the foundations act as secondary sources for pressure waves. The compressive waves also reflect from the free surface as tensile release waves increasing soil porosity.

As a result the interaction of the pressure waves in the soil with the gas main is also quite complex. These pressure waves on striking the pipe will wrap around it creating pressure maxima on the opposite side of the pipe. The waves will also be reflected by the pipe as waves with a cylindrical profile, which interact with the incident waves to form a complex loading pattern. The pressure loading will excite the various natural modes of vibration of the pipe. The pipe will therefore flex, twist and vibrate as a result of the loading.

The velocity field of the roof and on the vertical plane through the house, at 140ms, is shown in 3D and plane views in figure 3. The plot clearly shows the blast wave in the air that is perceived by an observer as the ‘bang’ and the velocity distribution of the roof. The motion of the pressure waves within the rooms’ generates the velocity ‘hot spots’ in the figure 3. The ejection of a window on the left of the figure, associated with a blast wave is also clearly shown.

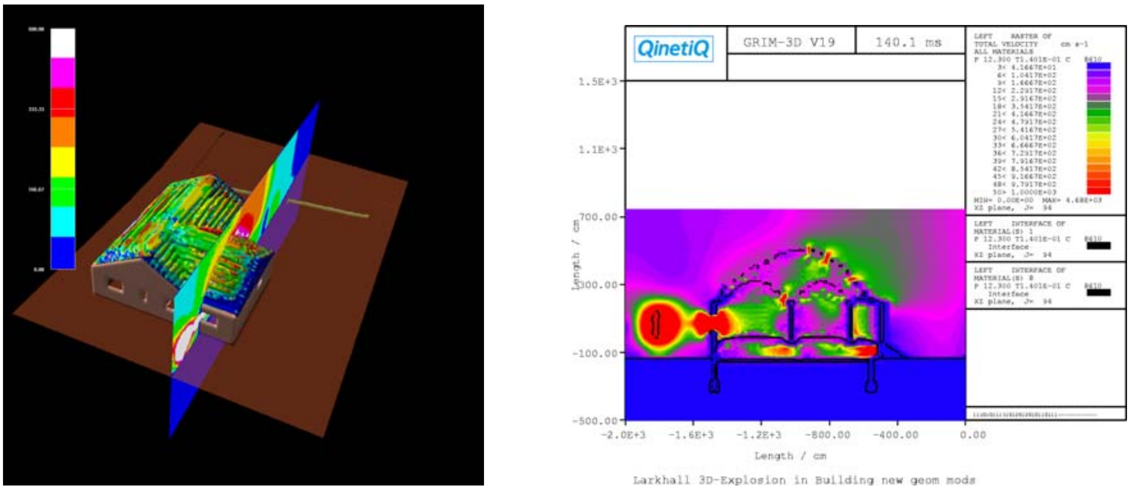

Figure 3. Velocity field in 3D (left) and plane view (right at 140ms.

Gas Main Response

The gas main structural response was simulated using DYNA3D, with the pressure-time histories generated by the GRIM3D solution.

The simulations contained some 120,000 computational cells and typically took 220 cpu hours to simulate the response of the pipe up to 60 ms, by which time the corroded region had failed in all scenarios investigated.

Loading Methodology

The internal pressure in the medium pressure gas main was given as 195 KPa (above ambient), and this pressure was applied to the interior surface of the gas main to pre-stress the pipe. This interior pressure causes an average hoop stress of 3.9MPa in the pipe, less than two thirds of the lower limit suggested for the corroded pipe. Once the pipe was in equilibrium with the internal gas pressures the exterior was loaded with dynamic pressure loads obtained from the dynamic simulation of the explosion of a methane/air mixture in the under floor void. The pressure loads, calculated in the GRIM3D simulation, were applied at the exact location of the defects described above (0.5m either side of the defects) over 10 degree sections and along the remainder of the pipe at 2m intervals to ensure appropriate loading conditions.

The dynamic pressure includes the contribution from the motion of the soil to the applied load on the pipe over and above that from the static pressure alone. In this case, however, it was found that the difference between static and dynamic pressure, due to the motion of the soil was not significant, partially due to the low velocity of the pipe and the proximity of the monitoring points to the pipe. The dynamic over pressure oscillated above and below ambient pressure as the pressure waves, identified above, impinged on the pipe.

Simulation Results

The medium pressure gas main structural response simulations showed that the corroded pipe failed for failure thresholds of 6MPa and 12MPa.

The dynamic pressure load applied to the pipe caused it to flex, both along the pipe and around its circumference. It was the stressing of the pipe in response to the variable applied load around and along the pipe that caused it to fail rather than a simplistic excess external pressure over the corroded region.

An example of the development of failure in the corroded region is shown in figure 4 for the defect in the simulation with a failure stress of 12MPa.

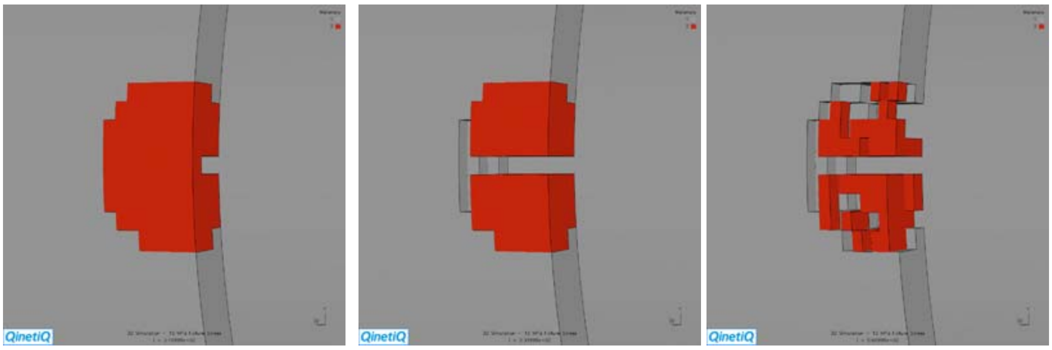

Figure 4. Example of failure development at 32ms, 45ms,and 57ms

The figure shows the initial formation of a horizontal (along the pipe) crack on the inside surface of the corroded region at 32ms (figure 5 left) and its evolution up to 57ms (figure 5 right).

The cracks occurred horizontally in defect 2. In defect 1, the crack occurred horizontally for the 6MPa failure case and vertically for the 12MPa failure case. Failure also generally occurred earlier in defect 2 than defect 1.

We also note that the pipe is failing at a very early time in the explosion energy, when 10% or less of the combustion energy of the explosion has been released and before the steepest part of the energy release profile. This suggests that even stronger corrosion product would also be likely to fail.

CONCLUSIONS

This report has described the 3D Eulerian and Lagrangian hydrocode simulations to study the interaction of a gas explosion in a domestic residence and a medium pressure gas main some 10 metres in front of the house.

The Eulerian code GRIM3D has shown that the interaction of the blast waves generated by the explosion of the gas in the under floor void with the geometry of the house and its foundations produces a complex source of pressure waves. These waves propagate away from the house and interact with the gas main and the surface of the soil.

The Lagrangian code DYNA3D, using the pressure loading on the pipes calculated by the GRIM3D simulation, has shown that the response of the pipe is sufficient to make the regions of graphitic corrosion with strengths of 6MPa and 12Mpa to fail .

The research has demonstrated that this methodology can be applied to a wide range of explosion scenarios and their interaction with buried structures.

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