18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18-J04-4

APPLICATIONS OF A COUPLED MULTI-SOLVER APPROACH IN EVALUATING DAMAGE OF REINFORCED CONCRETE WALLS FROM SHOCK AND IMPACT

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ABSTRACT

Sabotage from terrorist actions threatens the safety of nuclear power plants and materials. Physical barriers, usually made of steel reinforced concrete must be constructed around areas to be protected and must have adequate structural strength to prevent failure from terrorist threats. Two hypothetical terrorist threats are considered in the present paper: blast from the detonation of a truck bomb and impact from a Boeing 747 passenger jet. To simulate damage and failure of a thick steel reinforced concrete wall under such blast and impact loadings, a Coupled Multi-Solver approach based upon finite element and finite volume methods is applied. The three-dimensional numerical simulations are performed with the nonlinear dynamic analysis computer program AUTODYN®. The damage developed in the reinforced concrete walls from these threats is investigated and the most successful use of physical barriers is discussed.

Keywords: Numerical Simulation, Blast, Impact, Finite Element Analysis, Finite Difference Analysis

1. INTRODUCTION

Acts of sabotage are the major source of threats that must be considered in the design of nuclear power plants. The most disastrous types of sabotages are from terrorist actions such as the use of a vehicle bomb or the impact of large objects, including an airplane. In the recent terrorist attack in Istanbul, Turkey on November 20, 2003, two vehicle bombs detonated almost simultaneously at the British consulate and at the Hong Kong and Shanghai Banking Corporation (HSBC) headquarters. They left more than 20 people dead and hundreds of people injured. The most destructive terrorist action in history was in New York on September 11, 2001. Two large commercial passenger jet airliners impacted the World Trade Center buildings and took nearly three thousand lives.

To protect nuclear power plants and materials from such deadly terrorist actions, a physical protection system, also called physical barriers must be permanently built and properly maintained around nuclear power plants and materials. A system of physical barriers might consist of multiple barriers. The outside barrier is built at the perimeter of the protected areas while the inside barrier is provided by building walls such as those of a nuclear reactor or fuel storage building. An isolation zone is created between the outside and the inside barriers to clear all objects that could conceal or shield a person.

Physical barriers must have adequate structural strength against the threats from terrorist actions. They are required to protect any person standing directly behind the barriers from injury and prevent damage to equipment that could occur from complete demolition, projectile/fragment penetration or spalling of barrier materials. The physical barriers are usually made of reinforced concrete, so in the present paper a steel reinforced concrete wall is studied. The initiation and progressive development of damage in reinforced concrete walls under such blast and impact loadings is thoroughly investigated.

2. COUPLED MULTI-SOLVER APPROACH

In the past, analytical methods have been largely used to derive design loads for, and response to, small aircraft impacts on nuclear power plants or reactors. This kind of approach uses spring-mass-damper systems to simplify the complicated deformation state of nuclear power plants and the interaction between the deforming aircraft and structures. The single degree-of-freedom model developed in Kulak and Yoo (2003) is one of many works utilizing this analytical approach.

With today's increased computing power and improved simulation packages, three-dimensional numerical simulations based on finite element and finite difference methods are viable for simulating such extreme events. Numerical simulations can supply quantitative and accurate details of stress, strain, and deformation fields that would be very expensive, difficult, and often impossible to obtain analytically and experimentally. In the recent finite element simulations of Suanno *et al* (2003) and Kukreja *et al* (2003), the actual geometric shape of nuclear reactors was taken into consideration. The impact from the aircraft was approximated by a loading versus time curve derived from an analytical approach. The geometric shape and actual damage of the aircraft as well as interaction between the deforming aircraft and the structures were not taken into account in their simulations.

The numerical models used in simulations of structures under impact and blast loadings are very complicated in nature, involving different phases of materials (gases, liquids, and solids) and highly non-linear material and structural behavior (plasticity, large strain, and large deformation). For a proper investigation of such impact scenarios it is necessary to have modern numerical techniques that are capable of modeling all of the following phenomena: impact, damage, fracture, and structural response. To do this effectively requires multiple numerical solvers such as Lagrange, Euler, ALE, Navier-Stokes, and Meshfree techniques. Interaction and coupling between these different solvers can be used to provide the "best" solution in terms of accuracy and efficiency. We call this the Coupled Multi-Solver approach (Quan *et al*, 2003), which has been successfully implemented into a nonlinear dynamic analysis computer program AUTODYN® (CD, 2005 and Birnbaum & Cowler, 1987).

The interaction between two Lagrangian grids is called Lagrange/Lagrange interaction and is implemented in AUTODYN using impact/slide surfaces. The Coupled Multi-Solver approach with Lagrange/Lagrange interaction was successfully employed in Quan and Birnbaum (2002) to simulate the impact of a Boeing passenger jet to the New York World Trade Center North Tower and the progressive collapse of the North Tower. The predicted area of impact damage was in excellent agreement with visual observations on the exterior of the Tower after the airplane impact. The most recent work using a similar approach was Itoh, Katayama, and Rainsberger (2005) where the impact of an F-4 Phantom jetfighter into a reinforced concrete wall was simulated. Good agreement of impact force and damage area was achieved between numerical predictions and experimental measurements.

The interaction between Eulerian and Lagrangian grids is called Euler/Lagrange coupling, often used to simulate fluid/structure interaction or gas/structure interaction. Lagrangian grids overlap Eulerian grid and provide constraints to the flow of material in the Eulerian grid. At the Euler-Lagrange interface, the Lagrange grid acts as a geometric flow boundary to the Euler grid while the Euler grid provides a pressure boundary to the Lagrange grid. As the Lagrange grid moves or distorts, it covers or uncovers the fixed Euler cells. The coupled Euler/Lagrange technique allows complex gas-structure or fluid-structure interaction problems including large displacements and deformations of the structure, to be solved in a single numerical simulation.

The Coupled Multi-Solver approach with Euler/Lagrange coupling has been successfully applied to structures under blast loadings by researchers such as Luccioni, Ambrosini, and Danesi (2004) and Berg and Preece (2003). In Luccioni, Ambrosini, and Danesi (2004), the collapse of a 7-stories building following the detonation of a 400 Kg TNT charge inside the building was accurately reproduced in numerical simulations. The predicted damage in the building and its progressive collapse agree very well with the actual visual observation. In Berg and Preece (2003), the damage profile of a structure was simulated when an explosive detonated inside the structure. The overall deformation of the structure was in good agreement with the results from an analytical approach.

3. NUMERICAL SIMULATIONS

Using the Coupled Multi-Solver techniques in AUTODYN, three-dimensional numerical simulations were performed to investigate the damage in a thick reinforced concrete wall under blast loading from the detonation of a truck bomb as well as the impact from a Boeing 747 passenger jet airliner.

3.1 Steel-Reinforced Concrete Wall

The physical barrier studied in the present simulations is a rectangular steel-reinforced concrete wall modeled using Lagrangian solvers. The concrete material was modeled using the Lagrange solid solver and the steel reinforcing bars using the beam solver. The reinforced concrete wall is restrained from lateral motion at the bottom using a boundary condition.

For the blast analyses, the geometric size of the concrete wall is 60m wide, 30m high, and 1m thick. The Lagrange element size is 0.5m in width and height, and 0.2m in thickness. This creates a mesh of 121×61×6 or 36,000 Lagrange elements.

For the impact analyses, the geometric size of the concrete wall is 150m wide and 60m high to match the wing span of a Boeing 747 airplane that is 64m wide. In addition to the 1m reinforced concrete wall, a second 3m reinforced concrete wall is also included in the impact simulations. The center of the both concrete walls is meshed the same as the wall used in the blast simulations (0.5m). In the area surrounding the center part, the Lagrange element size of the concrete is increased to 1.5m in width and height. However, the element thickness is kept the same. The total number of Lagrange elements in the entire concrete material is thus increased to 56,000 in the 1m thick concrete wall and 186,000 in the 3m concrete wall. Lagrange transition elements are used to connect the two differently zoned regions.

The steel reinforcing bars are placed in two layers of a distance of 0.4m from the surface of the wall. In the blast analyses, there are 39 vertical and 19 horizontal steel bars. In the impact analyses, there are 99 vertical and 39 horizontal steel bars. The ratio of the reinforcement is 0.8%. The length of each beam element matches the surrounding Lagrange element size so the steel beam elements can be joined to the Lagrange concrete elements. Figure 1 shows the mesh of the reinforced concrete wall used in the impact analyses and the steel reinforcing bars inside the concrete.

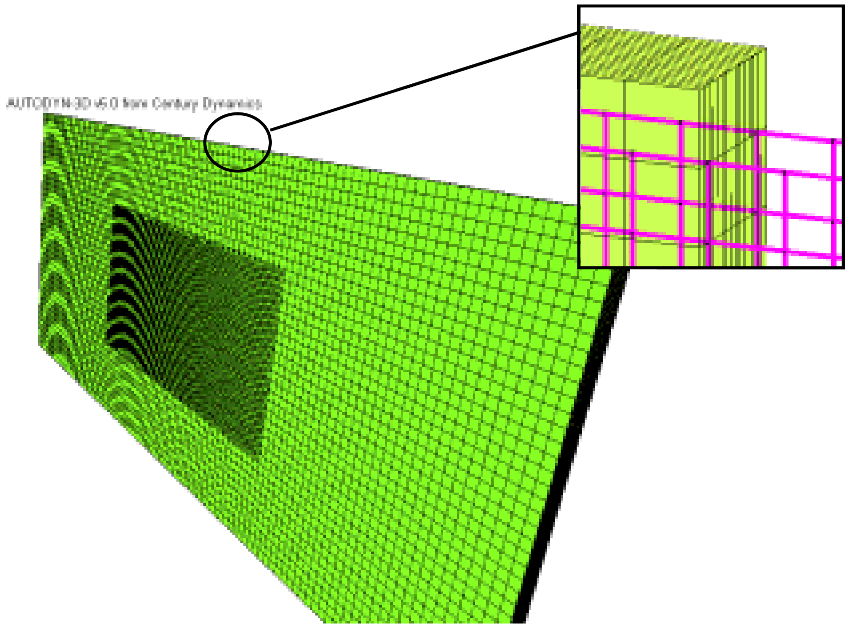


Figure 1 Mesh of the steel reinforced concrete wall (left) and steel reinforcing bars inside the concrete (right).

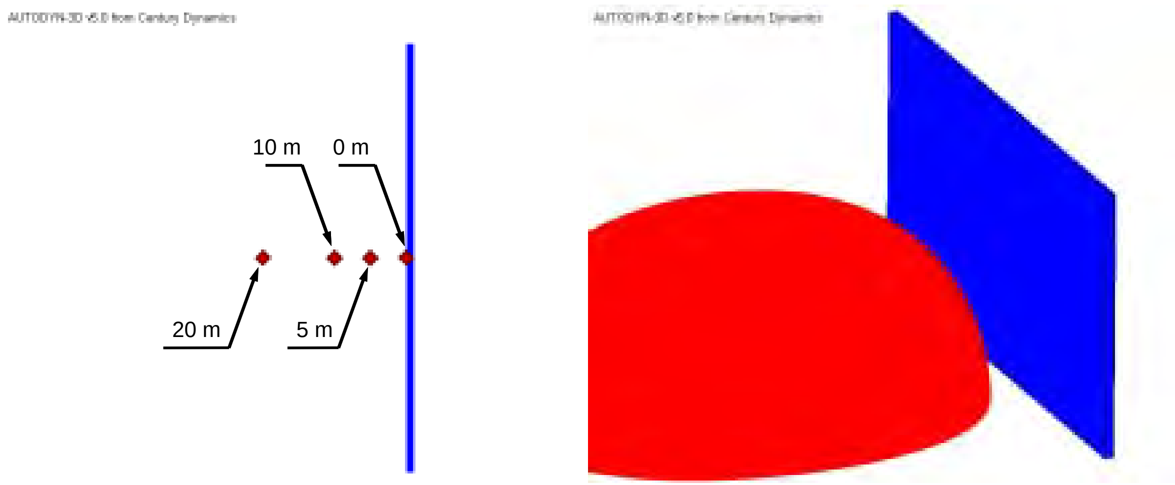
The RHT strength and failure model, a validated constitutive relation implemented in AUTODYN to describe the behavior of concrete under high pressure and high strain rate, is used for the concrete in the present simulations. A von Mises strength model is used to represent the steel reinforcing bars. Data for both materials can be found in Katayama, Itoh, and Rainsberger (2004).

3.1 Blast on the Reinforced Concrete Wall from Explosion of a Truck Bomb

The cargo volume of a general 4-wheel land truck is usually more than 200 cubic feet, *i.e.*, over 5m^3. The density of TNT is 1,630 Kg/m^3. Thus the amount of explosive that a typical truck can transport is very large. In the present simulations, a hypothetical truck loaded with 5,000 Kg TNT is assumed. Calculations are performed, with the TNT detonating at a distance of 0m, 5m, 10m and 20m respectively from the reinforced concrete wall as shown in Figure 2(a). The detonation at 0m is also referred to as contact detonation.

Except for the contact detonation, the detonation of the explosive TNT and subsequent spherical expansion of the explosive gas products prior to the blast reaching the wall are simulated in a 1D Euler analysis. This allows accurate modeling of the early stages of the blast and keeps reasonable element sizes for the later stages which are modeled in 3D. This unique capability saves a lot of computing time in the 3D calculations. The 1D calculation ends when blast wave almost reaches the front surface of the reinforced concrete wall. After the 1D calculation, the spherical blast field is then mapped into a 3D grid using an easy to use remapping capability developed in AUTODYN. Figure 2(b) shows the blast wave in the 3D model just after being remapped from the 1D analysis, where the truck bomb is placed 20m away from the reinforced concrete wall.

In the 3D model, the propagation, reflection, and diffraction of the blast wave are simulated with an Eulerian (Euler-FCT) solver while the structural deformation of the reinforced concrete wall is simulated using Lagrangian (Lagrange and Beam) solvers. In order to properly couple with Lagrangian solvers, the Euler-FCT part covers not only the entire reinforced concrete wall but also the space that extends 5m away from the top and sides of the reinforced concrete wall. The finite volume mesh of the Euler-FCT part is 201×121×81 in the 20m detonation, about 2,000,000 elements. Euler/Lagrange coupling is used to compute the coupling between the blast wave and the deforming structures.

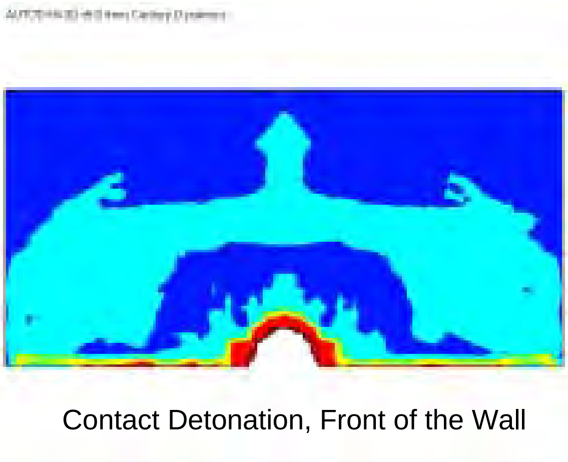


(a) (b)

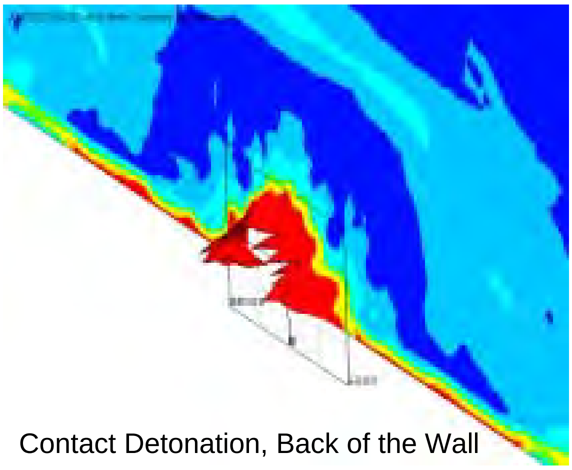
Figure 2 AUTODYN 3D model shows (a) the location of the truck bomb and (b) the blast wave just after remapped from 1D simulation, where the truck bomb is placed in 20m distance from the reinforced concrete wall.

The damage to the reinforced concrete wall one second after the explosive detonation is shown in Figure 3(a-f) for different blast scenarios and different perspectives. The damage in the concrete is measured by the ratio of the plastic (unrecoverable) strain to the ultimate strain limit of the material. In Figure 3, red shows areas where the material has completely failed (damage=1). The light blue color denotes partially damaged areas (0<damage<1). In the blast simulations, the back surface at the bottom of the concrete wall is damaged for all four cases. The magnitude of the damage decreases with the distance of the bomb from the wall.

For the contact detonation, Figure 3(a-b) shows extensive damage distribution on both front and back surfaces of the concrete wall. The reinforced concrete wall is completely perforated by blast from the explosive detonation. An opening 12m wide and 6m high is created in the wall. Thus this reinforced concrete wall fails to provide protections as a physical barrier against a contact charge.



(a)



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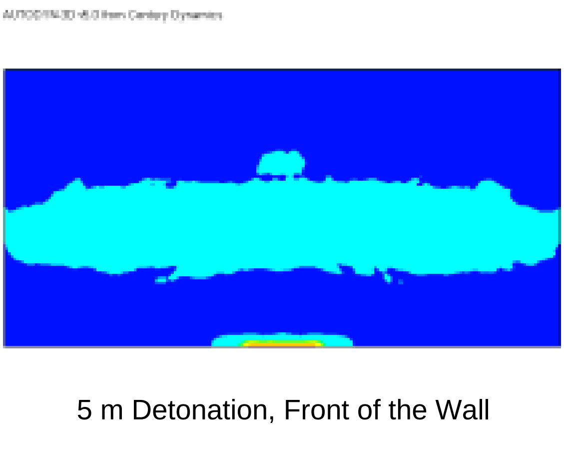

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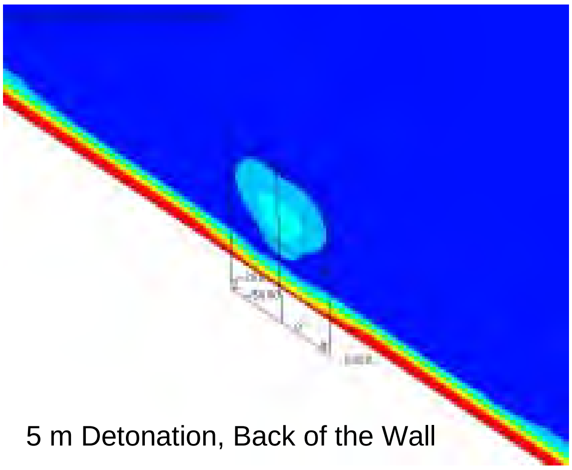

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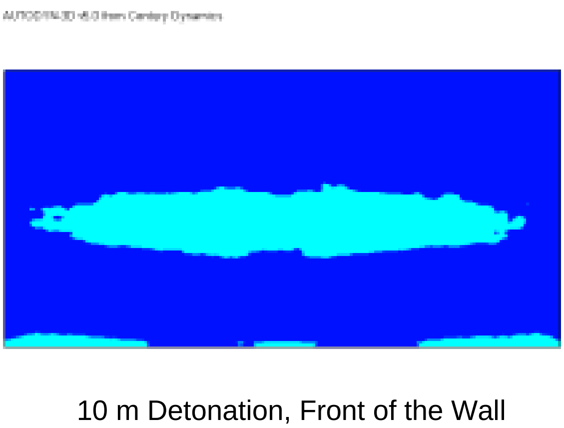

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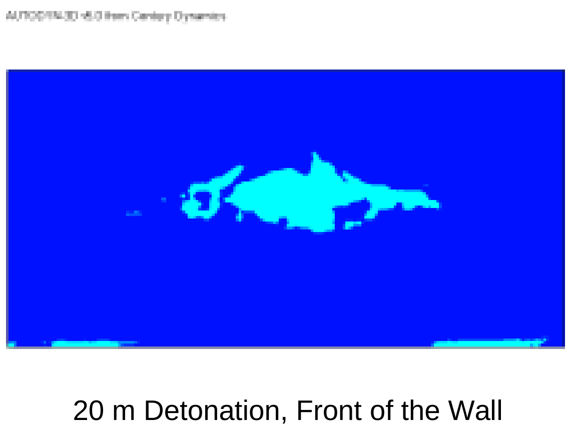


(f)

Figure 3 The damage of the reinforced concrete wall one second after the explosive detonation.

When the truck bomb detonates 5m away from the concrete wall, the wall remains intact, although it has a lot of damage on both the front and the back surfaces as shown in Figure 3(c-d). The partially damaged area on the back surface of the concrete wall is 10m wide and 6m tall.

When the truck bomb detonates 10m or 20m away from the concrete wall, there is very little damage on the back surface of the wall. Most of damage is on the front surface of the concrete wall as shown in Figure 3(e-f). Thus, the steel reinforced concrete wall does indeed protect personnel and equipment from the blast.

The damage shown in Figure 3 is caused only by the bare explosives. The effects of fragments of the truck engine and body as well as weakening of the steel reinforcing bars by possible fire are not considered in the present analyses. These effects probably are not likely to affect the conclusions from the 10m and 20m blast simulations, but might affect the results when the bomb is 5m or less from the steel reinforced wall.

When the truck bomb detonates 5m from the reinforced concrete wall, the back surface of the wall is damaged. The impact of truck fragments might cause further damage, perhaps more destructive, to the wall. The wall might be completely perforated by truck fragments. The concrete material at the back surface might spall due to the tensile stress wave created by the impact of the fragments. So, from the conservative point of view, this concrete wall should not be considered to withstand the detonation of the truck bomb as a physical barrier when the bomb is 5m away.

Figure 4 shows the time history of total energy deposited in the concrete material after detonation of the bomb. The total energy deposited in the contact detonation is twenty times higher than the total energy in the other three blast scenarios so it is not plotted in the graph. The interaction and coupling between the blast wave and the reinforced concrete wall mostly takes place in the first 0.25 seconds. When the blast wave reaches the front surface of the wall, the rear surface is still unpressurized, creating a pressure difference across the wall. This pressure difference drives the increase in total energy of the concrete. It appears as the initial rise of the total energy in Figure 4.

As the blast wave continues to expand, it diffracts at the edges of the wall, and propagates into the region behind the wall. The pressure on the back surface of the wall increases, so that the pressure difference across the wall decreases. This reduced pressure difference slows down the motion of the wall and causes the drop in the total energy after its initial rise. The drop is more significant in the 5m and 10m detonations than the 20m detonation due to the higher strength of the blast wave with the closer distances.

Finally, after the blast wave passes through the concrete wall, the pressure on the back surface of the wall decreases. Thus the wall accelerates to create the second rise in the total energy of the concrete. As the blast wave propagates beyond the wall, the loading drops off and the total energy of the concrete levels off.

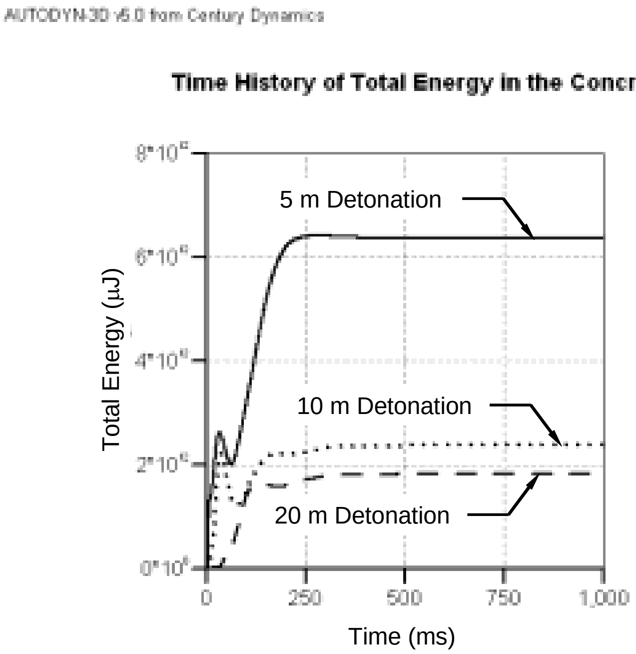


Figure 4 Time history of total energy in the concrete after detonation of the truck bomb

3.2 Impact on two Reinforced Concrete Walls by a Boeing 747 Passenger Jet

A Boeing 747 passenger jet airliner is selected as a hypothetical impact threat. The mesh was created in True*Grid* (XYZ, 2004) based on CAD geometry, then imported into AUTODYN.

The AUTODYN shell solver was used to represent the entire airplane. The thickness of the shell elements was adjusted so the overall weight of the entire airplane and weight distribution among the fuselage, engines, and fuel were correctly represented. The impact velocity of the airplane was 83.3m/s (300km/h), slightly above its landing speed 77.8m/s (280km/h). The Johnson-Cook strength model was used to model the aluminum. The property data used for aluminum can be found in Katayama, Itoh, and Rainsberger (2004).

The 3D AUTODYN simulation model is shown in Figure 5. Lagrange/Lagrange interaction was applied in the model to exchange forces and momentums between the interacting structural parts of the airplane, concrete, and reinforcement.

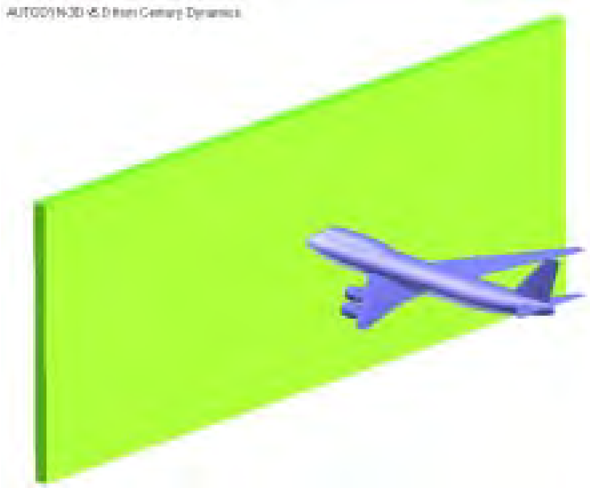


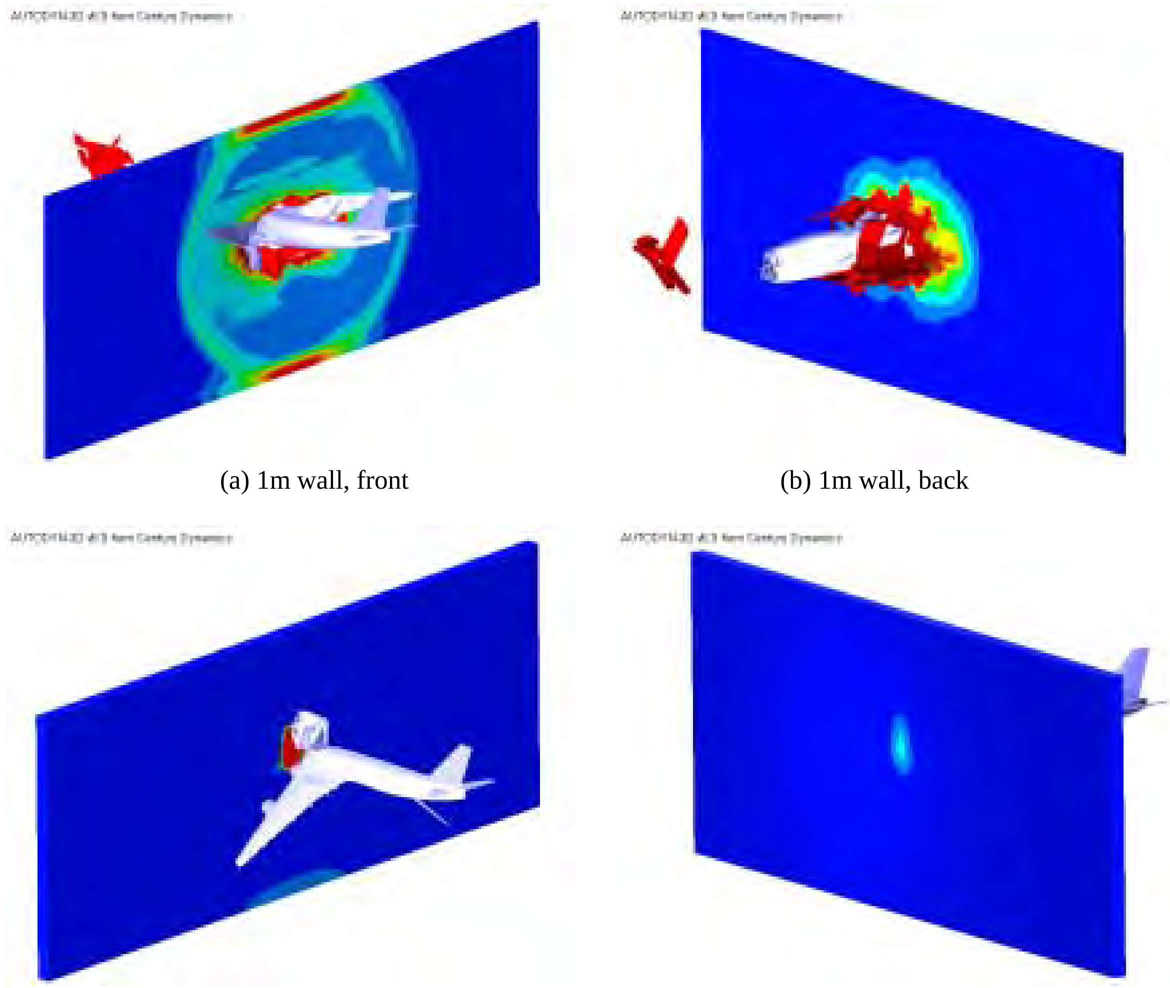
Figure 5 AUTODYN 3D model of a Boeing 747 passenger jet airliner impacting a 3m thick steel reinforced concrete wall.

The 1m thick steel reinforced concrete wall is completely perforated by the airplane as shown in Figure 6(a-b) with extensive damage to the wall. Therefore, the 1m thick concrete wall cannot withstand the impact of such an airplane and cannot provide protections as a physical barrier against such impact.

In the next impact simulation, a 3m thick steel reinforced concrete wall replaces the 1m thick wall. At one second after the impact, the airplane fuselage buckles and the entire airplane crushes on the front surface of the concrete wall as shown in Figure 6(c-d). The impact damage is localized and concentrated in the immediate area of the impact site. The wall remains intact and stands up to the airplane impact. To provide protection with a physical barrier against the impact of such airplane, the thickness of the reinforced concrete wall has to be increased to 3m (assuming the same ratio of reinforcement).

4. CONCLUSIONS

The damage and failure of a typical physical barrier of reinforced concrete wall, subjected to blast from the detonation of a bomb and the impact of a Boeing 747 passenger jet, has been successfully studied in AUTODYN using the Coupled Multi-Solver approach with Lagrange/Lagrange interaction and Euler/Lagrange coupling. The relationship between damage of the reinforced concrete wall and the distance of the truck bomb from the wall is discussed. The effect of the thickness of the reinforced concrete wall on the impact of a Boeing 747 passenger jet is demonstrated. The ability to simulate various threats against a variety of protection systems provides insight into the most important physical phenomenal taking place. This insight can be leveraged to design the most cost effective yet safe protection barriers.



(a) 1m wall, front (b) 1m wall, back

(c) 3m wall, front (d) 3m wall, back

Figure 6 Damage of concrete at one second after the airplane impacts the steel reinforced concrete wall.

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