Blast Damage Assessment to a Modern Steel Structures

Eric Mestreau [1], Joseph D. Baum [1], Chuck Charman [2], Seung Lee [3] and Young Sohn [3]

[1]Science Applications International Corporation, McLean, VA, 22102, USA, baumj@saic.com
[2]General Atomics, San Diego, CA, 92121, USA, charman@dat.com
[3]Defense Threat Reduction Agency, Alexandria, VA, 22060, USA, young.sohn@dtra.mil

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ABSTRACT

The terrorist attack of September 11th 2001 has enforced a new examination of the response of modern steel structures, such as those found in large warehouses, auditoriums and airport terminals, to a terrorist bomb attack. The effort described in this paper assesses the potential damage to such a newly designed structure from a medium-size car bomb. The structure is mostly composed of a lightweight complex beam structure with large windows and skylights piercing through a corrugated roof. The structural response to the terrorist attack requires the modelling of various physics phenomena including bomb detonation, blast wave propagation, reflections, and refractions and resulting blast impact on the structure. Hence, a fluid/structure coupled methodology is used to perform the assessment.

The Coupled CFD/CSD Numerical Methodology

The flow solver employed is FEFLO98, a 3-D adaptive, unstructured, edge-based hydro-solver based on the Finite-Element Method Flux-Corrected Transport (FEM-FCT) concept [L? 2]. It solves the Arbitrary Lagrangean-Eulerian (ALE) formulation of the Euler and Reynolds-averaged turbulent, Navier-Stokes equations. The high order scheme used is the consistent-mass Taylor-Galerkin algorithm. Combined with a modified second-order Lapidus artificial viscosity scheme, the resulting scheme is second-order accurate in space, and fourth-order accurate in phase. The spatial mesh adaptation is based on local H-refinement, where the refinement/deletion criterion is a modified H2-seminorm [L? 2] based on a user-specified unknown. Most of the shock wave propagation cases require the use of a blend of density and energy. FEFLO98 supports various equations of states including real air, water, SESAME and JWL with afterburning. Particles can also be used. They are treated as a solid phase, exchanging mass, momentum and energy with the fluid.

The structural dynamics solver is DYNA3D [Wh91], an unstructured, explicit finite element code. DYNA3D is well suited for modeling large deformations and provides a good base for non-linear materials with elasto-plastic compartmental laws with rupture. DYNA3D incorporates a large library of materials and various equations-of-state, as well as many kinematic options, such as slidelines and contacts. Furthermore, DYNA3D is a well proven and benchmarked solver used extensively in the CSD community.

Parallelization Issues: The coupled methodology uses shared memory across O(500) CPU뵬 using open-MP standard. As we typically encounter many partitions (CFD FEM, CFD particles, CSD FEM, CSD contacts, fluid-structure coupling, CTD), while conducting transient problems with large CPU load variations, MPI would have been very expensive for frequent mesh redistribution, adaptation, and remeshing. In addition, as the main focus of our efforts has been maximizing the physical realism, we prefer to optimize the algorithms for the physics of the individual disciplines, maximize the performance on the individual processor, and provide low cache misses, pipelining, and vectorization.

Modeling of terrorist Attack on a steel Structure

The effort described in this paper assesses the potential damage to a newly-designed steel structure from a medium-size car bomb. The structure is mostly composed of a lightweight complex beam structure with large windows and skylights piercing through a corrugated roof.

Figure 1a shows an overview of the complete neam structure, whiles Fis 1b and 1c show interanl views within the facility showing the complex beam structure and the corrugated roof. All beams are modeled as segments within the DYNA3D model, except for the central main column facing the blast. The beams modeled by segments are typically not loaded by the shock. This is a valid approximation as long as the beam thickness is small, as the shock wraps around those beams very quickly, equalizing the pressure surrounding them. The resulting load is far too small to be of any consequences for this simulation. To address damage concerns, the main four columns nearest the blast are modeled with shells. Such representation allows these four columns to be loaded not only by the connecting beam structure but also by the direct blast. All the beams have a Young Modulus of 30,000,000 psi with a yield strength of 36,000 psi.

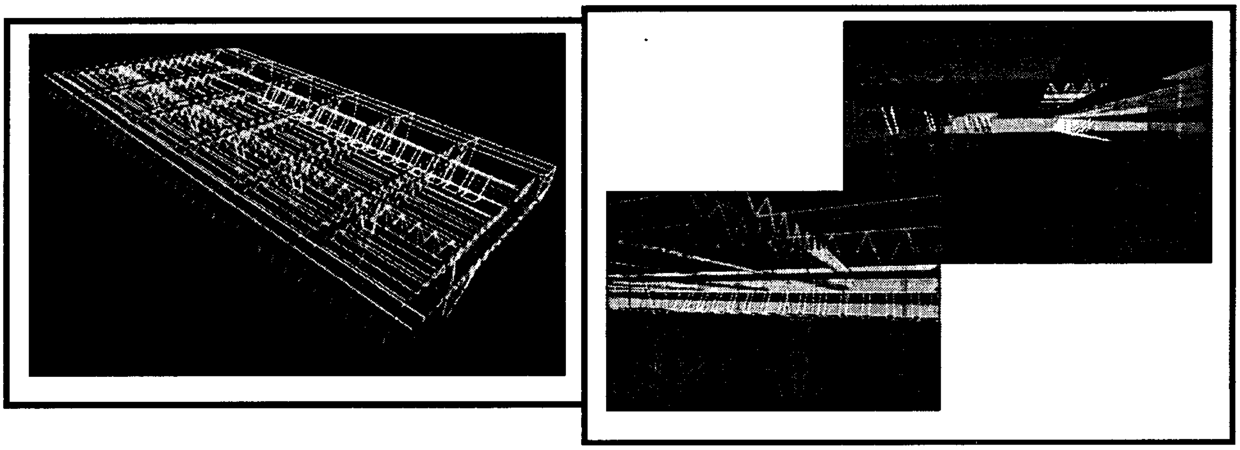


Fig 1. a) The CSD Model ? beams Structure (colored by types and sections); Figs1b and 1c: internal views within the facility.

Fig 2. Corrugated Roof, disjointed plates are alternatively colored green,blue. White plates are just moved up for display.

The roof is modeled with separate plates riveted to each other every 18? and to the underlying trusses and purlins. There are two ways to model such corrugated roof with DYNA3D: using anisotropic shells to account for the difference of stiffness in the two main axes or accurately modeling the real geometry of the roof. The second option was chosen for this model. The roof is built from flat plates welded to a trapezoidal configuration sitting on top of it. The weatherproofing and insulation material are taken into account and distributed as added weight over the nodes of the roof structural model.

The CFD mesh contains about 33 million tetrahedral elements, 6 million points and about 200,000 boundary points. The complete structural model contains a total of about 580,000 nodes, 580,000 shells and 31,000 bars. In addition, the model contains about 5,200 rivets, 12,500 welding spots and about 100 beam/beam connections (mostly for the rear-end of the trusses and the purlins-to-trusses connections). Sliding interfaces have also been specified, especially at the end of the trusses to obtain the correct structural behavior in the case of failure of the bolts representing the brackets. Translation and rotation constraints have been added to the vertical column bases of the section behind the counters.

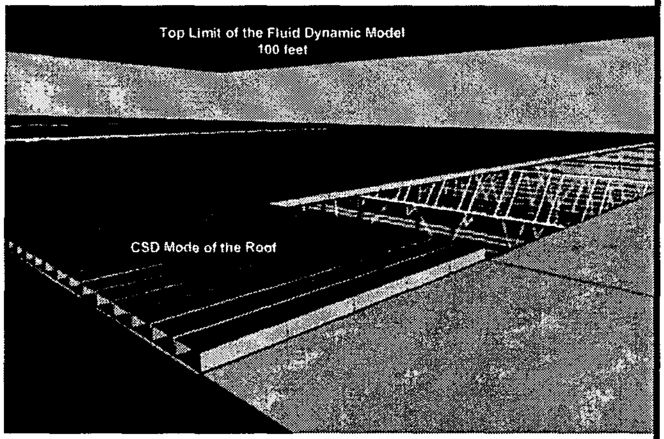
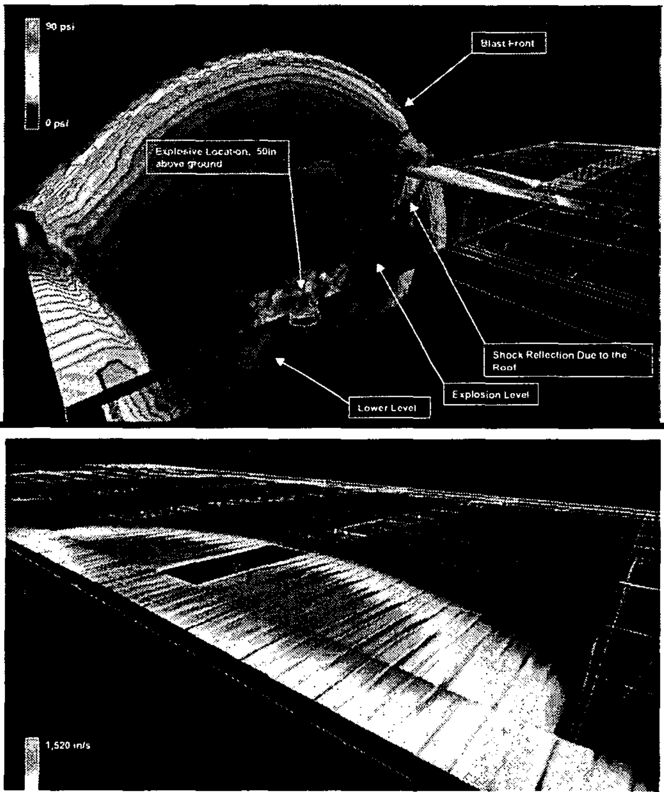


Fig 3. CSD Roof and CFD Roof

The CFD model covers the main and lower levels of the structure. The continuation of the roof between the CFD and CSD models (Fig 3) is required to provide a correct blast expansion beyond the structural model. In this region, the roof is modeled as rigid boundary.

The charge was placed at car height some distance in front of the strutcure. At 18ms, the shock has already reflected from the back virtual back wall? Figure 4 presents the CFD pressure contours in the middle cut-plane and on the CSD roof structure and shows the shock trace on the floor main level. Several shock reflections on the roof structure are also shown. These results also depict the shock reflection (green bottom left) from the back wall. The incident shock has reached the two nearby trusses, one on each side of the middle plane of symmetry.



Figs 4. Pressure and velocity contours at 18ms.

At the end of the simulation, the shock has reached beyond the structural model in all directions. The velocity results (Fig 5) show the complete corrugated roof lifting off the supporting beams. The maximum velocity of 1,000 in/sec is still located at the front section of the roof. Most of the panels are flying off flat except for those whose rivets have failed non-uniformly, resulting in an additional rotational movement. The rear section of the roof beyond the large skylight is also lifting off.

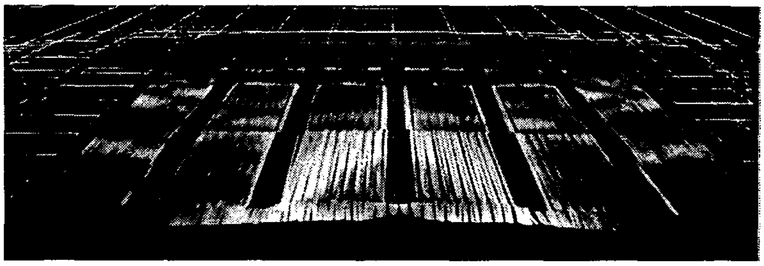


Figure 5: Roof Displacement with Velocity Contours

While some sections of the beam structure, noticeably the connecting truss and the I-beam supporting the rear of the trusses, suffer high stresses of about 16,000 psi, it is far from the yielding stress. The purlins have reached their peak stress levels and now oscillate as indicated by the negative velocity of the central portion of the beam (Figure 7). After the shock wave passage over the rear section of the roof, the back purlins above the counters are also accelerated upward with velocities reaching 182 in/sec. The local stress peaks at about 16,000psi.

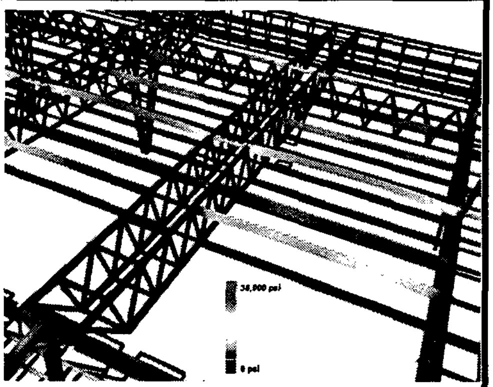


Figure 6: Maximum Stress

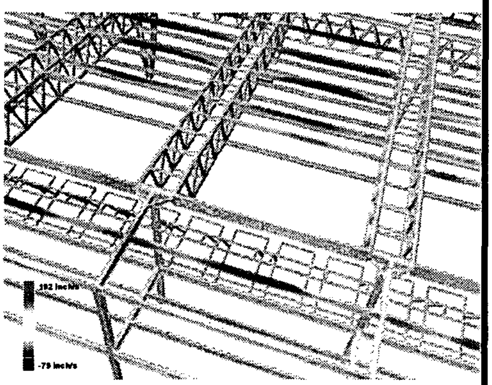


Figure 7: Vertical Velocity (positive = up)

The beam structure does not receive directly a heavy load from the blast waves. Due to their small cross-section, the pressure differential between the front and the back is quickly reduced, leading to a small load capable of only creating vibrations within the elastic regime. The corrugated roof takes most of the load with the gradual rupture of the attached rivets, imposing a vertical pull on the underlying beam structure. The resulting stress is only large enough to have a few non vital perlins reach plasticity. The easily replaceable corrugated roof is the only resulting damage of significance but the integrity of the structure remains intact. If the structure had been constructed with large concrete columns and walls close to the explosion, the results could have been very different.

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