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FSI SIMULATIONS FOR EXPLOSIONS VERY NEAR REINFORCED CONCRETE STRUCTURES

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Abstract. The analysis of explosives in contact or very near to reinforced concrete (RC) structures is an important aspect in the design of protective structures and vulnerability assessments. Although this remains a topic of high importance for defence, a more widespread interest has developed as civilian structures become the targets of terrorism. This type of assessment requires a robust simulation method for coupled fluid-structural interactions (FSI) which can handle the explosive detonation, air blast propagation, structural deformation, and damage evolution. This paper describes the application of a loose-coupling method which combines the FEFLO CFD code and SAIC's CSD code for 3D numerical simulations of unconfined and semi-confined explosions near RC structures. This approach takes advantage of the unstructured tetrahedral mesh for the CFD and an embedded method for CSD structures inside the fluid domain. Comparisons of simulations with experiment provide validation, but also reveal some weaknesses of the method. A good agreement between simulation and experiment is found with moderate explosive loading. However, a severe explosive loading with confinement results in extensive damage to the structure which is difficult to reproduce in simulations.

1 INTRODUCTION

In this work, we focus on the prediction of damage to reinforced concrete (RC) structures from the detonation of high explosives. In particular, we are interested in scenarios where the explosive is very near or in contact with the concrete. This presents a challenging problem for simulation as there is significant deformation and damage of the structure which will alter the blast flow field and it becomes crucial to capture the fluid-structure interaction (FSI) phenomena. To accomplish this, we use a loose-coupled method which combines computational fluid dynamics (CFD) and computational structural dynamics (CSD) techniques.

Our current work focuses on the assessment of the loose-coupled FSI method through comparison with experiments. We follow the simulation methodology established by SAIC for high strain-rate and large deformation response of concrete structures during blast and impact scenarios [1]. First, we investigate a moderate blast loading on a single concrete slab to indentify an appropriate set of model parameters. Then we test how well the same set of parameters and simulation method works for moderate and severe semi-confined explosive loading of a more complex RC structure.

2 NUMERICAL APPROACH

2.1 Fluid-Structure Interaction (FSI) methodology

The simulations use a loose-coupled approach which combines previously validated and established CFD and CSD codes through a controller code [2]. Alternatively, a strong coupled method would require a completely re-written single coupled code. The disparity in stiffness and timestep between the fluid and solid domains also creates difficulties for a strong coupled method.

The position and motion of the solid inside the fluid domain is handled with an embedded approach. This has several advantages over a glued-mesh approach. In particular, the CFD and CSD surface meshes do not have to be matching at the interface, which prevents problems created when tracking fragments or the breakup of the solid structures [3]. Figure 1 shows the basic FSI approach with exchange of information between the CFD and CSD codes via the controller code [1, 4].

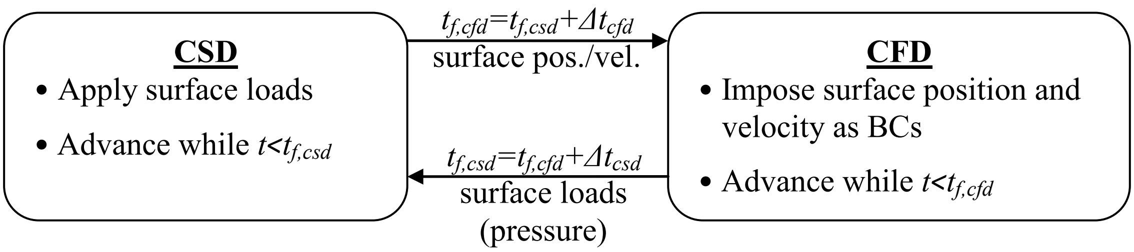

Figure 1: General CFD/CSD coupling procedure during simulation. Each code calculates its own timestep (Δt) and continues from the final time (t_f) of the other code in a staggered manner.

2.2 Computational Fluid Dynamics (CFD) solver

The FEFLO98 code is a 3D, unstructured, edge-based fluid dynamics solver using an Arbitrary Lagrangian-Eulerian (ALE) formulation of the Navier-Stokes and Euler equations. The code uses the FEM-FCT method for shock capturing which has been well-established for applications involving explosions and shock propagation around complex geometries [3, 4]. The explosive is modeled using the Jones-Wilkins-Lee (JWL) equation of state with a programmed burn detonation model and the air is modeled with a “Real Gas” EOS (nonconstant gamma behavior).

2.3 Computational Structural Dynamics (CSD) solver

The structural solver employed is the SAIC-CSD code which uses an explicit second order finite element method. The primary features applicable for RC simulations are [1]:

- Fully-integrated Q1/P0 solid elements
- A large strain rate (FE) convective formulation
- The K&C phenomological plasticity model for damage in the concrete
- Embedded method for reinforcement bars inside solid concrete elements
- Numerical damping to avoid spurious velocities near failed elements
- A general contact algorithm using bin technology for fast node-face searching operations
- All procedures are fully parallelized with a quasi-optimum speed-up on shared memory architectures

The K&C concrete plasticity model has been highly validated for concrete subjected to explosions, impact, and high strain rate events. This material model has three independent strength surfaces (yield, failure, and residual) with consideration of all three stress invariants (I_1, J_2, and J_3) [5]. Additionally, there is an extension of the plasticity model in tension and a radial path strain rate enhancement which are critical for producing accurate simulations of concrete under rapid loading conditions. The modified plastic strain λ is calculated separately for compressive or tensile loading by:

$$\lambda = \begin{cases} \int_0^{\bar{\varepsilon}_p} \frac{d\bar{\varepsilon}_p}{r_f\left(1 + \mathrm{p}/r_f f_t\right)^{b_1}} & \text{for p} \geq 0 \\ \int_0^{\bar{\varepsilon}_p} \frac{d\bar{\varepsilon}_p}{r_f\left(1 + \mathrm{p}/r_f f_t\right)^{b_2}} & \text{for p} < 0 \end{cases} \tag{1}$$

where p is pressure, and the effective plastic strain increment is defined as $d\bar{\varepsilon}_p = \sqrt{\left(\frac{2}{3}\right)\varepsilon_{ij}^p \varepsilon_{ij}^p}$. This also accounts for the strain rate enhancement r_f (dynamic increase factor, DIF) of the concrete which is based on the modified CEB formulation [6]:

$$DIF_{conc} = \begin{cases} \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{\delta} & \text{for } \dot{\varepsilon} \leq 1\ s^{-1} \\ \beta\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1/3} & \text{for } \dot{\varepsilon} > 1\ s^{-1} \end{cases} \tag{2}$$

where $\dot{\varepsilon}_s$ is a constant, and parameters δ and β are functions of the concrete yield strength. As λ increases, the K&C model damage parameter η will increase from 0 to 1 at λ_m and then decrease back to 0. A scaled damage variable is then calculated by [7]:

$$\delta = 2\lambda/(\lambda + \lambda_m) \tag{3}$$

The steel is modeled with a bilinear elasto-plastic material and employes a similar form of strain rate enhancement [8]:

$$DIF_{steel} = \left(\frac{\dot{\varepsilon}}{10^{-4}}\right)^{\alpha} \quad (4)$$

where α is a function of the steel yield strength. The reinforced bars are modeled by embedding beam elements into solid hexahedral elements during the CSD initialization. During each simulation time step, the kinematic variables (displacement, velocity, and acceleration) of the "slave" embedded re-bars are interpolated from the "master" solid element's degrees of freedom, and their internal forces are applied back to their respective master elements by a standard finite element extrapolation.

3 NUMERICAL SIMULATIONS

3.1 Explosion near a concrete slab

A validation of the loose-coupled method was performed by comparing simulations with experimental work described in Zhou *et al.* [9]. The test consisted of a 0.5kg Comp-B charge located 10cm above a 1-way reinforced concrete slab which had dimensions of 100x130x10cm and was clamped along the short edges. The concrete strength was 50MPa and steel rebar assumed properties of ASTM Grade 60. The simulations utilized one plane of symmetry and were run on 4 to 16 CPU of an SGI-Altix system. A similar element size between the CFD and CSD domains was maintained as shown in Figure 2a.

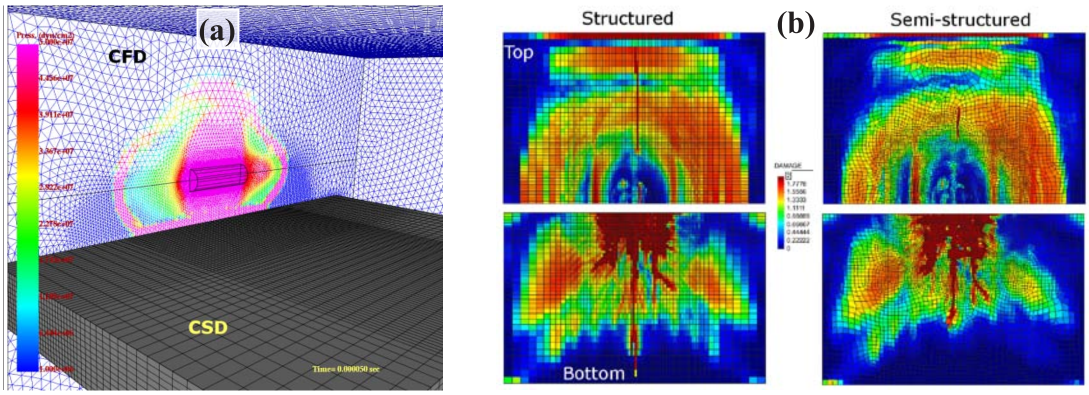

Figure 2: Blast loading on the concrete slab showing CFD and CSD discretizations (a). Comparison of concrete damage variable on the top and bottom surfaces using structured and semi-structured 8-node elements (b).

The validation models were used to investigate the influence of mesh, material, and element parameters on the simulations results. A comparison of simulations using structured and semi-structured 8-node solid elements for the concrete shows some influence on the predicted damage (Fig. 2b). Defining areas of mesh refinement was easier with a semi-structured mesh. The structured mesh produced element failure along straight paths which was questionable. However, a structured mesh with uniform element size was useful when the damage locations are not known *a priori*. Decreasing the element size resulted in a finer resolution of damage paths in the concrete, and also increased the localized damage and element failure. A small change in CSD/CFD element size very rapidly increased the total number of elements and computational resources required which can become restrictive. Table 1 demonstrates this, and also reveals that number of elements for the CFD was at least an order of magnitude larger than the CSD.

Table 1: Number of elements for the CSD, CFD, and ratio of CFD/CSD for three levels of mesh refinement. "Size" refers to the dimension of the smallest CSD elements (at the slab center).

Mesh	Size	CSD	CFD	Ratio
Coarse	8mm	5.10E+04	3.46E+06	67
Medium	6mm	1.18E+05	4.65E+06	39
Fine	4mm	3.88E+05	8.20E+06	21

Other important input parameters were the damping fraction α and the concrete maximum damage value δ_{max} which triggers element erosion (when $\delta_{max} > \delta$) [1]. It was found that a few combinations of δ_{max} and α in simulations produced a reasonable agreement with experiment. However, keeping α as low as possible was desired to avoid unrealistic over-damping of the structural response. Values of $\alpha = 0.05\text{-}0.1$ and $\delta_{max} = 1.90\text{-}1.95$ gave the best results. The same set of parameters determined from this validation study were applied to the more complex semi-confined structures.

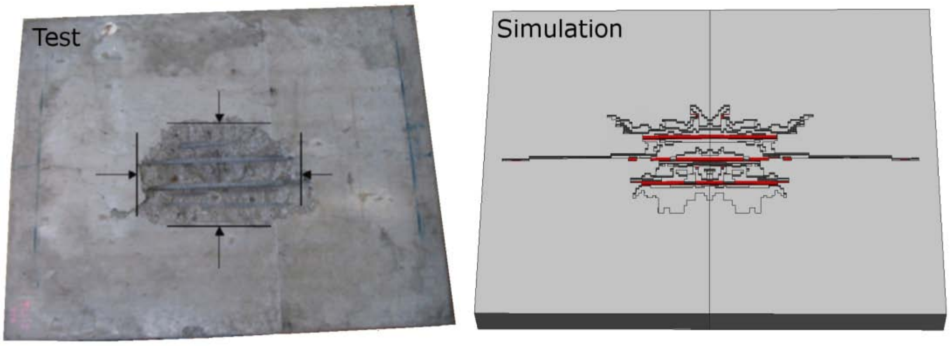

Figure 3: Comparison of damage to the bottom of the concrete slab observed in the experiment (image reproduced with permission)[9] and simulation (α=0.1, δ_{max}=1.90).

3.2 Semi-confined explosions inside RC structures

The semi-confined explosion tests consisted of two slabs with different thickness separated by columns at the corners. An explosive charge of TNT was placed in contact with the bottom slab. A complex arrangement of three rebar types (different steel strengths and bar diameters) provided reinforcement in the structure. Using the embedded rebar approach, the complete rebar configuration was constructed and modified independently from the concrete structure in the pre-processing. This makes it considerably faster to develop the RC model compared to the more traditional approach of constructing a single part containing both the steel and concrete materials and adjusting element sizes to match the rebar size. The simulations utilized two planes of symmetry and were run on 4 to 16 CPU of an SGI-Altix system.

The test structure was subjected to a moderate explosive loading which produced spalling, a small through-hole in the top slab, and a larger hole in the bottom slab. For this case, the simulations were able to predict the extent of damage and relative size of the damaged areas. The simulation results are shown at 5 ms, (Fig. 4c), after the blast loading and damage to the structure was complete.

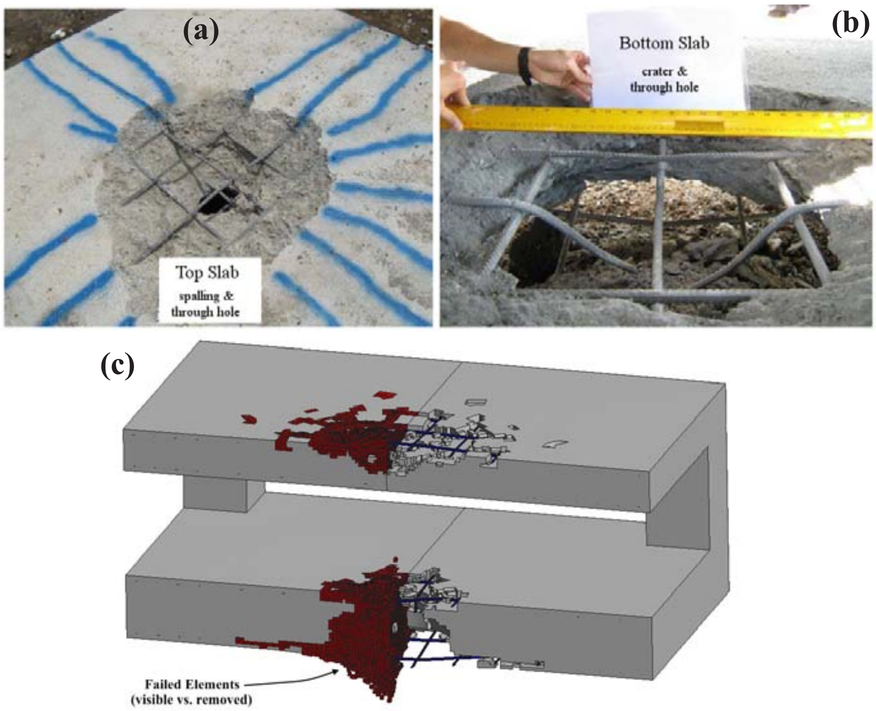

Figure 4: Damage comparison for a moderate explosive loading scenario. Test results (a,b) and simulation with visualization for half of the structure (c).

Next, a more severe explosive loading scenario was investigated which consisted of a larger charge in a similar structure having an additional edge beam around the top slab. The edge beam provided more confinement for the blast which increased the structural loading. In this case, there was extensive damage to the structure with the entire top slab removed and columns destroyed. There was also a through-hole produced in the bottom slab and a large amount of deformation and damage to the rebar. Initial results of the simulations (5ms) show a reasonable prediction of the bottom slab through-hole size while the top slab and columns remain intact. However, simulations run beyond this time have a large amount of failed elements without the removal of the top slab or rebar damage observed in the test (Fig. 5a).

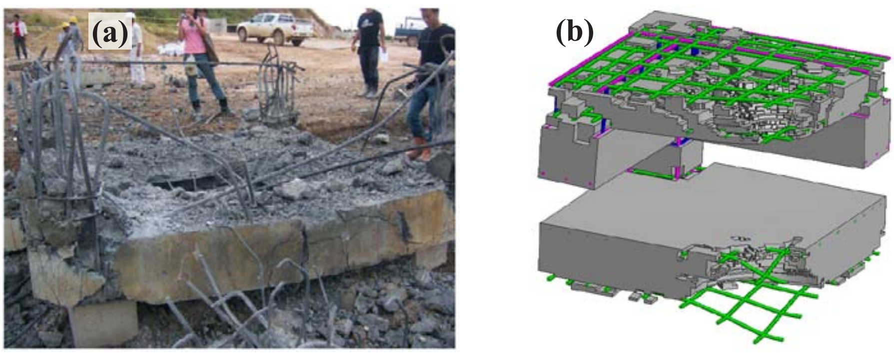

Figure 5: Damage comparison for a severe explosive loading scenario. Test results (a) and simulation at 5ms (b).

3.3 Treatment of failed concrete elements

Once a concrete element has failed, the internal nodes are duplicated and the element is allowed to fly free from the structure. The failed CSD elements can either be invisible to the CFD or have their surfaces sent to the CFD to interact with the flow field. Passing the failed concrete CSD surfaces to the CFD solver can become very computationally expensive as the number of failed elements increases during simulation, and is usually not necessary.

In the case of the severe loading or a confined blast, the gas can escape through the holes created in the concrete and prematurely reduce the structural loading. Two simulations of the severe loading scenario were used to compare the difference when failed CSD elements were invisible to the flow and when they interact with the flow. The differences in the blast pressures and inclusion of the failed CSD surfaces can be observed in Figure 6. As the number of failed concrete elements increases, the difference in computational time becomes apparent. At 5ms, the speed of the simulation with failed CSD elements in the CFD (Fig. 6b) was reduced to approximately 50% of the original (Fig. 6a) on the same number of CPU. Interestingly, the final damage observed in the two simulations was essentially identical. This implies that the pressure reduction due to the hole formed in the concrete is not significant to the overall structural loading.

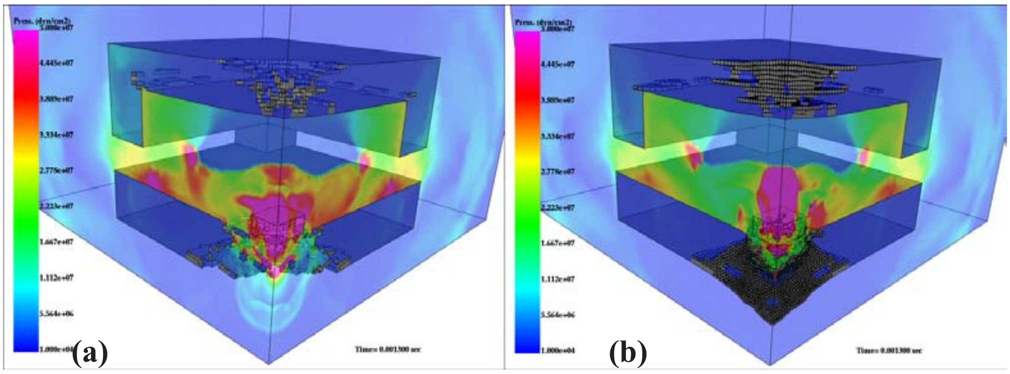

Figure 6: Pressure contours on the symmetry planes and CSD surfaces passed to the CFD solver for simulations without (a) and with (b) failed concrete elements.

In actual RC structures, the rebar provides a large amount of strength for the structure and acts as a cage keeping the damaged concrete fragments from flying apart. Using the embedded rebar approach, once the concrete element containing a rebar beam is failed then the exposed rebar does not interact with the CSD elements or CFD flow. That is, the failed concrete elements will “float” through the exposed reinforcement bars. This lack of interaction between failing structural components could contribute to the under-prediction of damage observed in the simulations for the severe loading scenario. A possible solution to this limitation is to use solid elements for the rebar inside the concrete, but at increased model complexity and computational expense.

5 CONCLUSIONS

This work has demonstrated the ability of the loose-coupled CFD/CSD method with a solid-embedding technique for simulating explosions near RC structures. The primary observations made through this work are:

- Preliminary simulations for validation and parameters studies are essential in determining the best set of solver, material, and mesh parameters.
- Simulations for the moderate explosive loading of a concrete slab and a semi-confined RC structure have good agreement with damage observed in tests.
- Simulations for the severe explosive loading of a semi-confined RC structure are initially able to predict the extent of damage, but under-predict the amount of damage to the structure and rebar at later times.
- Including failed CSD concrete elements as individual flying bodies in the CFD flow increases computational cost significantly, and does not noticeably alter the predicted damage to the structure.
- Treatment of rebar by embedding beam elements in solid concrete elements method does not account for the interaction of exposed rebar with other CSD elements or CFD pressures.

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