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# Using Coupled Eulerian and Lagrangian Grids to Model Explosive Interactions with Buildings

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# USING COUPLED EULERIAN AND LAGRANGIAN GRIDS TO MODEL EXPLOSIVE INTERACTIONS WITH BUILDINGS

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## ABSTRACT

This paper presents the development of a computational model that can be used to study the interactions between structures and detonating explosives contained within them. This model was developed as part of an effort to develop a rubble characterization model for use in AmmoSIM, an agent based urban tactical decision aid (UTDA) software for weapon-target pairing. The rubble pile created following the collapse of a building in a combat situation can significantly impact mission accomplishment, particularly in the area of movement and maneuver. The information provided by AmmoSIM will enable both platoon level and command center staff to make informed decisions concerning urban attack tactics.

Computational models were created using a combination of AUTODYN 2D and 3D. The detonation was modeled using a 2D wedge, which is a common method used in AUTODYN. The information obtained from the wedge calculation was then written to a data file and subsequently remapped into a larger 3D Euler air grid. The air grid loaded with blast pressure information was coupled to interact with the Lagrangian building parts. The Riedel, Hiermaier and Thoma (RHT) Concrete Model from the AUTODYN material library was utilized to create the components of the building. Results of the latest models will be given. Additionally, the paper details the development of the model at length including topics such as grid sizing, computational cost comparisons, grid interactions, multi-solver coupling, strain erosion, and material parameters and selections.

## 1. INTRODUCTION

The modeling process described in this paper was a portion of a larger effort to develop an urban tactical decision aid (UTDA) called AmmoSIM. The UTDA software being developed by 21CSI will have the capability of exploiting 3-D urban terrain data and evaluating the impacts of urban terrain to help commanders make decisions regarding mobility, fields of fire/observation, obstacles, cover/concealment, fire hazards, command and control, etc.

AmmoSIM is intended to be an "on-the-fly" simulation tool to predict/validate weapons effects and employment against targets in an urban environment. As such, 21CSI is developing it to include rubble effects, breakout of fires, infrastructure degradation, and WMD/HASMAT effluent patterns. Rubble impacts mission accomplishment, particularly in the area of movement and maneuver. Rubble characteristics must be known, for example, in order to predict ability of a vehicle to override the collateral damage from weapon effects in urban areas.

A computer-based numerical model of building response using AUTODYN was developed to support analytical models that were also developed during this project. A series of 20 increasingly complex simulations were performed with the end result being a complete model of a two story building with 4 rooms on each floor as seen in Figure 1. This paper is a topical overview of the development of the numerical model beginning with explosive characterization and ending with post processing of model using visual tools such as videos and still pictures at important times during simulations.

One of the unique aspects of this particular model development is the use of grid coupling. The practice of coupling Euler grids to Lagrangian grids has become a possible solution to fluid to solid interactions appropriately. Euler grids are effective for fluid and gas calculations; however, they are not well suited for calculations for the behavior of solids. Lagrange grids are more suitable for solid calculations, while they can be quite ineffective for gases (Fedkiw, 2002). With recent advances in software such as AUTODYN, modelers have been enabled to couple grids more easily.

The broad scope of the project necessitated the use of several simplifying assumptions to begin the process of computationally modeling a real situation. Recognizing the

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many configurations of building materials and construction techniques used worldwide, a specific set of building parameters were selected to limit the complexity of the problem. These assumptions were made with intent to keep the modeling process as realistic as possible so that it is useful to 21CSI and the Army. The initial model was confined to monolithic concrete without reinforcement, and room and wall dimensions were standard throughout the building. Also, charge location was limited to the center of any room in the building configuration.

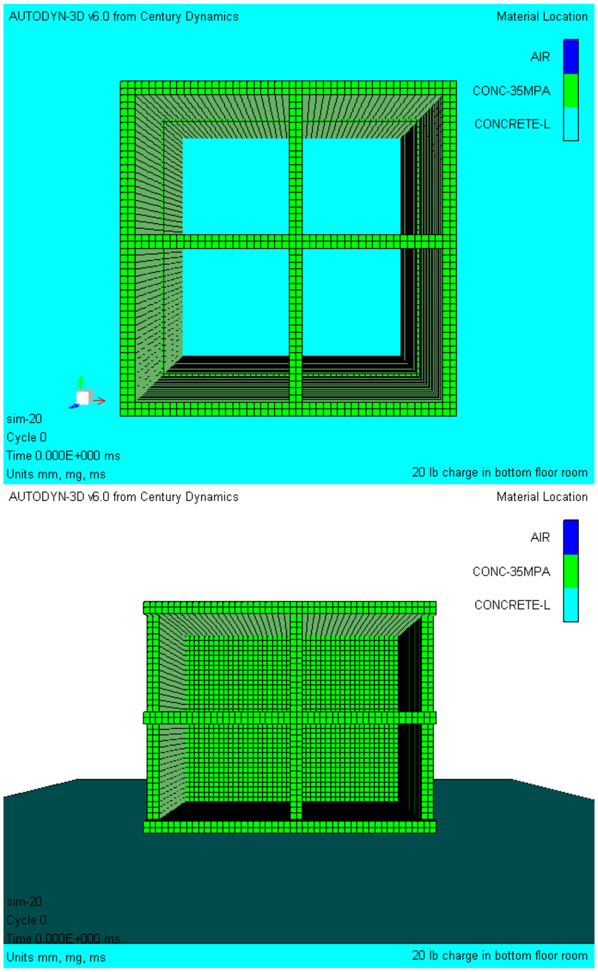


Fig. 1 Footprint of the final model building with room divisions (Top), as well as the vertical cross section of the building (Bottom).

## 2. MODELING PROCESS

The models were created using a combination of AUTODYN 3D and AUTODYN 2D. The detonation was modeled using a 2D Eulerian wedge which is a common method used in AUTODYN. The information obtained from the wedge calculation was then written to a data file and subsequently remapped into a larger 3D Euler grid of air. The air grid loaded with blast pressure information was coupled to interact with the Lagrangian building parts. The Riedel, Hiermaier and Thoma (RHT) concrete model from the AUTODYN material library was used to create the components of the building.

In order to generate blast pressure information for remapping into a 3D Euler grid, a technique known as a 1D Wedge was utilized. This function in AUTODYN allows the user to generate blast pressure information mapped into a wedge grid which can be rotated on its axes to create a sphere of blast pressure with certain properties. This sphere of blast pressure is then remapped into the larger, more computationally intense 3D Euler air grid.

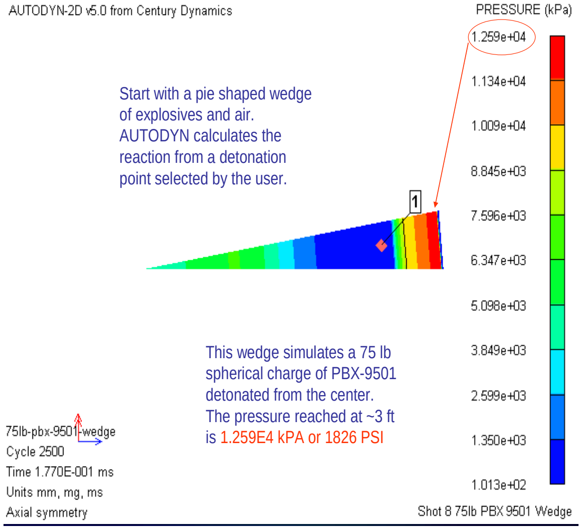
To create the wedge, charge size, overall wedge size, and charge type must be selected. Wedge calculations for this project used either TNT or PBX-9501 from the AUTODYN material library as the explosive charge. The wedge creation began with a chosen charge size. The overall wedge size is bounded on the lower end by the size of charge selected, and to avoid expansion errors, must allow for expansion of the explosive charge to ten times the original charge volume during the wedge calculation. Once the gasses and explosives have expanded to ten times their original value, the mix behaves similar to an ideal gas and its response can be more easily computed via an Ideal Gas EOS. Thus, the remapped information attenuates adiabatically according to the Ideal Gas Law once it is written into the 3D Euler grid. The upper bound for the wedge size is the size of grid into which it is remapped. The sphere of blast pressure information must not be allowed to overlay any Lagrangian components in the coupled model.

As an example, consider the placement of a charge in a cubic room with dimensions of 3 m per side. From the above considerations, this room size would bind the wedge radius at 1500 mm if the charge were placed in the center of the room. The procedure for creating wedge calculations in AUTODYN is therefore as follows.

1. Select charge size.
2. Calculate volume of charge in spherical condition.
3. Back calculate charge radius.
4. Select overall wedge size considering charge expansion and room dimensions.
5. Run wedge calculation.
6. Write data file for remapping.

In the 20 simulations performed as part of this study, several charge sizes were used, and a wedge calculation was performed for each. Figure 2 shows the original wedge grid for a 75 lb PBX-9501 charge with the legend for pressures found within the wedge. The results of the wedge calculations (~1826 PSI) are reasonable when compared with experimentally based calculations from the

DDESB (DOD Explosives Safety Board) Blast Effects Computer which predicts a pressure of 1793 PSI (Swisdak, 2003).



Start with a pie shaped wedge of explosives and air. AUTODYN calculates the reaction from a detonation point selected by the user.

This wedge simulates a 75 lb spherical charge of PBX-9501 detonated from the center. The pressure reached at ~3 ft is 1.259E4 kPA or 1826 PSI

Fig. 2 Wedge Calculation

Figure 3 is a rendering of the blast pressure information as it is remapped into the building model for SIM 20. The charge used in SIM 20 was a 20 lb TNT charge. The visual rendering consists of a ball of velocity vectors radiating from the center of the charge.

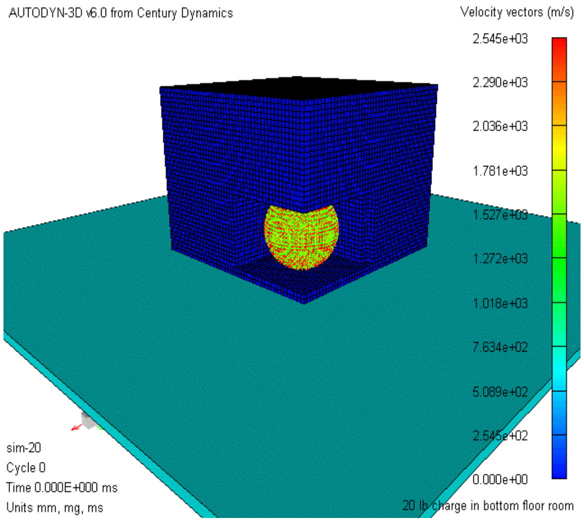


Fig. 3 Remapped sphere of blast pressure coupled with SIM 20

Once the characterizations of the explosive events were completed, the models in the simulations were developed using multiple coupled solvers. The simulations began quite simply, and evolved into the full two story building shown in Figures 1 and 3. While not every simulation will be described in detail, Table 1 shows a topical summary of each simulation model. Important breakthroughs and key models will be detailed in subsequent paragraphs of this section.

Table 1. AmmoSIM Autodyn Simulations Summary

| AMMOSIM AUTODYN Simulation Summary | | |
|---|---|---|
| **SIMULATION** | **Charge Description** | **Solvers** |
| SIM 1 | 5 lb. TNT | SPH/Euler |
| SIM 2 | 5 lb. TNT | LaGrange/Euler |
| SIM 3 | 5 lb. TNT | LaGrange/Euler |
| SIM 4 | 5 lb. TNT | LaGrange/Euler |
| SIM 5 | 75 lb. PBX 9501 | LaGrange/Euler |
| SIM 6 | 75 lb. PBX 9501 | LaGrange/Euler |
| SIM 7 | 75 lb. PBX 9501 | LaGrange/Euler |
| SIM 8 | 5 lb. TNT | LaGrange/Euler |
| SIM 9 | 5 lb. TNT | LaGrange/Euler |
| SIM 10 | 5 lb. TNT | LaGrange/Euler |
| SIM 11 | 75 lb. PBX 9501 | LaGrange/Euler |
| SIM 12 | 10 lb. TNT | LaGrange/Euler |
| SIM 13 | 10 lb. TNT | LaGrange/Euler |
| SIM 14 | 10 lb. TNT | LaGrange/Euler |
| SIM 15 | 10 lb. TNT | LaGrange/Euler |
| SIM 16 | 20 lb. TNT | LaGrange/Euler |
| SIM 17 | 10 lb. TNT | LaGrange/Euler |
| SIM 18 | 10 lb. TNT | LaGrange/Euler |
| SIM 19 | 20 lb. TNT | LaGrange/Euler |
| SIM 20 | 20 lb. TNT | LaGrange/Euler |

As mentioned above, the project required the use of many assumptions to limit the complexity of modeling a real world situation. The never ending combinations of building materials and construction styles did not allow for a complete analysis of all possible situations. The model was confined to monolithic concrete without reinforcement, and room and wall dimensions were constant throughout building configurations. The room dimensions selected for the simulations were 3m x 3m x 2.4m with 0.3m thick walls. Also, charge location was limited to the center of any room in the building configuration.

For the majority of the simulations, the walls were created using a Lagrangian grid with the Riedel, Hiermaier, and Thoma (RHT) concrete material model. The RHT material was selected from the AUTODYN material library (following advice given by Century Dynamics, the developers of AUTODYN). The RHT Concrete Model is a modular strength model for brittle materials developed at the Ernst Mach Institute. It has shown good results with other modelers, and is now being widely used for modeling concrete with AUTODYN (Century Dynamics, 2004). This material model handles many material failure issues including pressure hardening, strain hardening, strain rate hardening, third invariant dependence for compressive and tensile meridians, and damage or strain softening.

As the simulations progressed, the solvers and material model parameters remained unchanged, with the exception of a strain erosion cutoff level imbedded within the RHT model. Changes in the simulations involved grid size, charge size, solver coupling settings, Lagrangian joins and interactions, and other AUTODYN settings that affected the quality of the results produced.

Grid sizing is one of the most important decisions that must be made with simulations of this nature. Ideally, the grid should be as fine as possible. However, that would result in a very large computational cost, that is, a lot of time would be required to run the model. Clearly, there must be a balance between the computational cost and the results provided by the chosen grid. For example, in Table 1, SIM 2 was created with a very fine grid (Lagrangian cell Size = 60mm), but the model ran for 3 days before reaching 81 ms. This was not an acceptable computational cost for the initial models being created.

Once a prototype model is created, there is a possibility that a fine grid model could be run using all the parameters developed through using less costly grid sizes. With this in mind, the grid size in SIM 3 was expanded greatly to a cell dimension of 300mm. Figure 4 shows the Lagrangian grid created for SIM 3 as well as the air grid that overlays the walls. The time for running this model to over 1 second was reduced to less than one day by the reduction in grid size. While the reduction in Lagrangian cells was not inherently large, it is the Euler grid that is coupled with the Lagrangian walls that carries the majority of the cell count. When coupling Euler and Lagrangian parts in this fashion, the Lagrangian cell size should be at least two (2) times that of the corresponding Euler cell. This will allow for two Euler cells to interact with one Lagrangian cell. Since the Euler grid is a cube that surrounds the Lagrangian walls, changes in cell size significantly impacted the number of cells contained within the grid.

It is appropriate to discuss the computational costs of the model in perspective. The focus of this project was to determine the final configuration of a rubble pile following a structures reaction to an explosive load. While in most cases, finer grids (much finer than the 150mm fine grid defined in this paper) provide more detailed results, these results are not always more accurate. The scope of the project defines the problem in a way such that the final resting place and overall failure modes of the building are far more important than the precise modeling of their breakup. Most numerical models are designed to maintain a high level of detail at the cost of computational time due to ultra fine grids. In this case, a larger grid proves more effective.

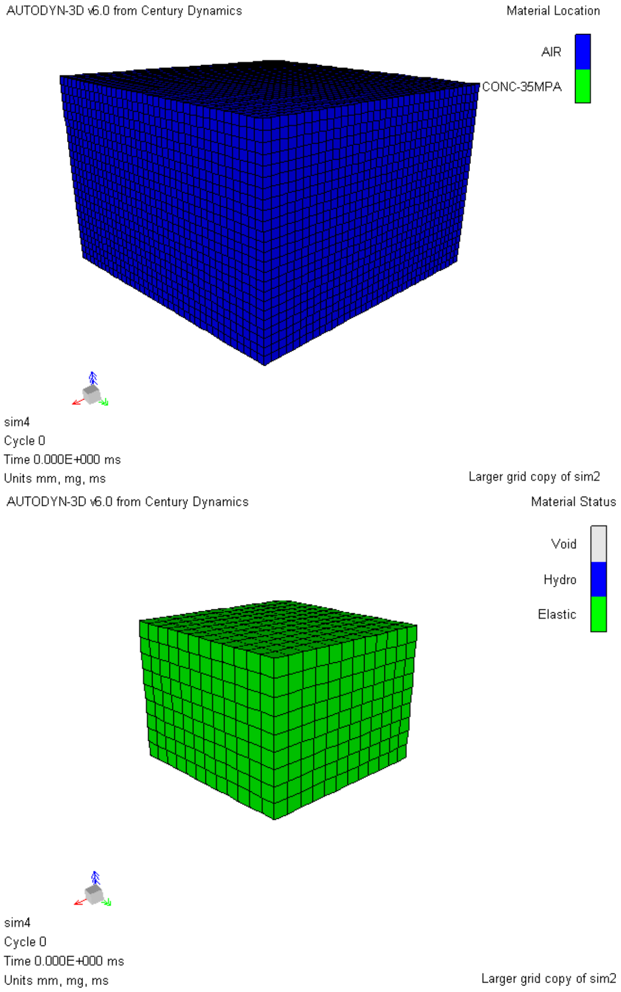


Fig. 4 SIM 3 Top – Air Euler grid overlaying Coarse Grid Concrete Model. Bottom – Concrete Lagrangian Parts

After several iterations and comparisons of visual results in the form of videos form the simulations, we determined that a 300mm Lagrangian cell size was too coarse. It did not provide reasonable breakage of the walls, and created fragments that were not appropriate for the type of loading placed on the parts. A cell size of 150 mm was utilized beginning with SIM 9. This cell size provided more reasonable results while not increasing the computation time to unreasonable levels.

The first four simulations in the series did not provide results worthy of note; however, during these simulations, many AUTODYN parameters were set to appropriate levels. These advances allowed for results to become more coherent and closer to reality as the simulations continued to evolve. Since the ability of a 5 lb. charge to cause damage to a room of the configuration modeled in the initial simulations was marginal, a much larger charge was used to calibrate the model before returning to smaller charges. SIM 5 was the first model that coupled all grids and interacted properly without errors in AUTODYN. As shown in Figure 5, a stretching phenomenon not characteristic of concrete resulted in SIM 5. This realization necessitated the inclusion of strain erosion in the model to enable fragmentation to occur without this stretching.

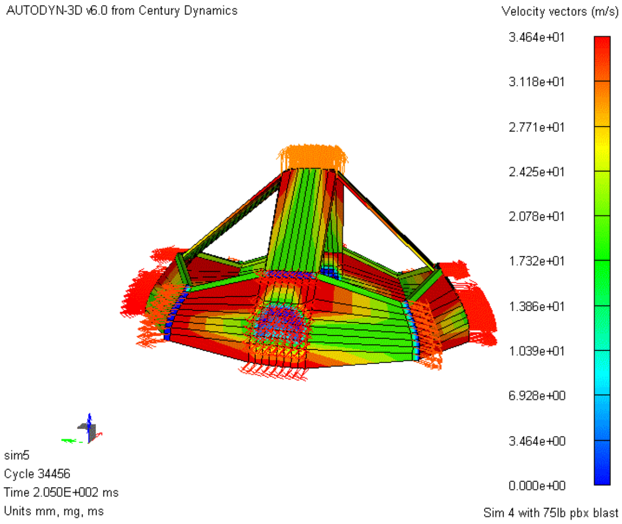


Fig. 5 Final result of SIM 5.

Strain erosion allows for the grid to remove cells and transfer momentum, energy, etc to adjacent cells. This removal of cells from the grid allows for fragmentation and eliminated the grid stretching phenomenon shown in Figure 5. Strain erosion settings are found in the material properties of the RHT Concrete model. In SIM 7, a strain erosion value of was entered into the RHT material to allow for the fragmenting of the concrete walls. The end results of SIM 7 without grid stretching can be seen in Figure 6.

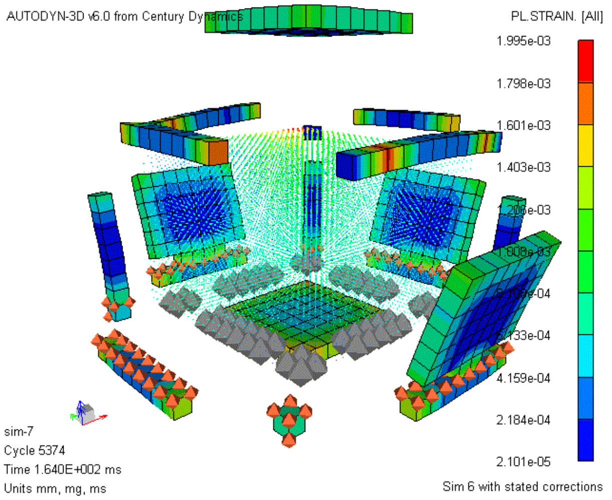


Fig. 6 Intermediate Result of SIM 7 with Strain Erosion

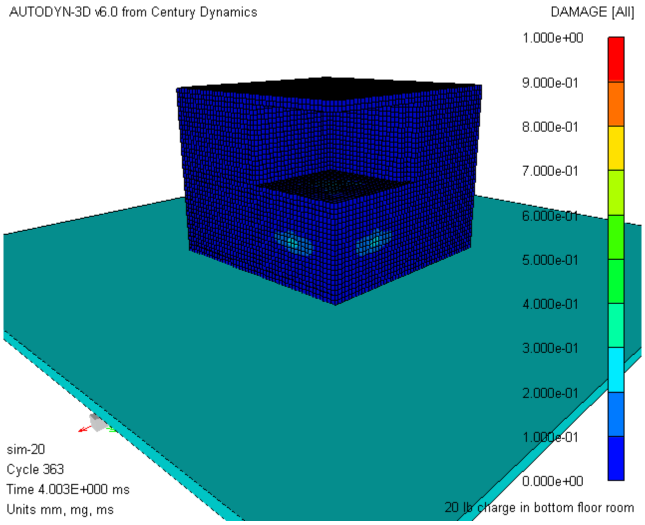
Strain erosion enabled the model to assimilate reality more effectively, but the correct strain erosion level had to be determined using post processing options in AUTODYN. Several additional calculations were run to identify the correct strain erosion; however, these calculations will not be discussed in this paper.

Throughout the model development, a major goal was to determine the size of charge necessary to completely reduce the room in the model to rubble, and subsequently feature this room in a larger model of a multistory, multi-room building. Through multiple iterations using varying charge sizes, grid sizes, and increasingly robust AUTODYN settings, a 20lb. TNT charge was found to effectively destroy the single room, while not throwing fragments thousands of feet. In reality, the optimum charge size for destroying a single room in this model lies somewhere between 10 and 20 lbs; however, since 20 lbs provided appropriate results, refinement of this value was not necessary. In addition, this charge size fits nicely into the upper range of weapon systems to be considered by the AmmoSIM System.

After 18 simulations, comfort with the results of each simulation was high enough so that a more complex model was planned for SIM 19. SIM 19 was the first model to be run with multiple rooms. The simulation included eight rooms. The building consisted of two floors with four rooms on each floor. The configuration for SIM 19 is similar to that seen in Figure 1. Additional features were added to the model for SIM 20 including a ground surface for allowing a rubble pile to form.

## 3. END RESULTS

The final simulation in the series made use of all the information gathered running all of the previous simulations. SIM 20 is a model built up from SIM 16. The final product is a two story building with 4 rooms on each floor. The grid and room configurations can be seen in Figure 1. The Euler air grid that was loaded with blast pressure information was placed in one of the bottom floor rooms, and allowed to interact with the surrounding walls. A large fill part without interaction was added to the bottom of the building to act as the ground and create a resting place for the rubble. Without this part, fragments would fall endlessly due to gravity. The explosion caused failure of the room due to the explosive forces, and the floor and roof directly above the loaded room began a toppling failure due to gravity. From basic commercial demolition principles, this is an appropriate response of the structure. With taller buildings, rooms other than those directly above the blast might be affected as well. Figure 7 shows a sequence of screen captures from SIM 20 showing the building response to the 20 lb TNT blast.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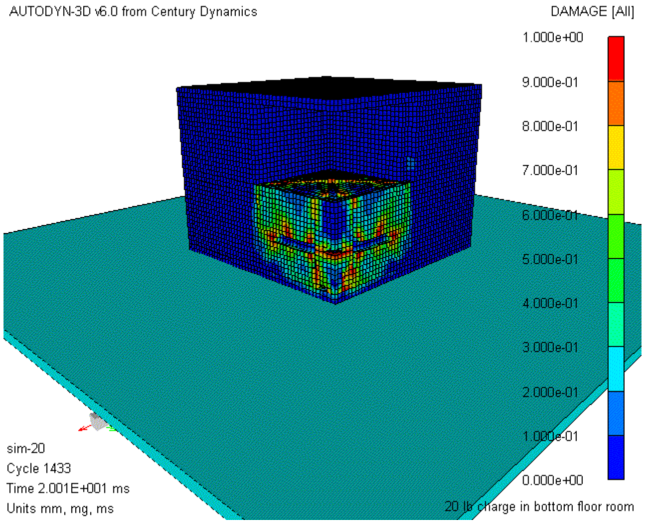
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Units mm, mg, ms
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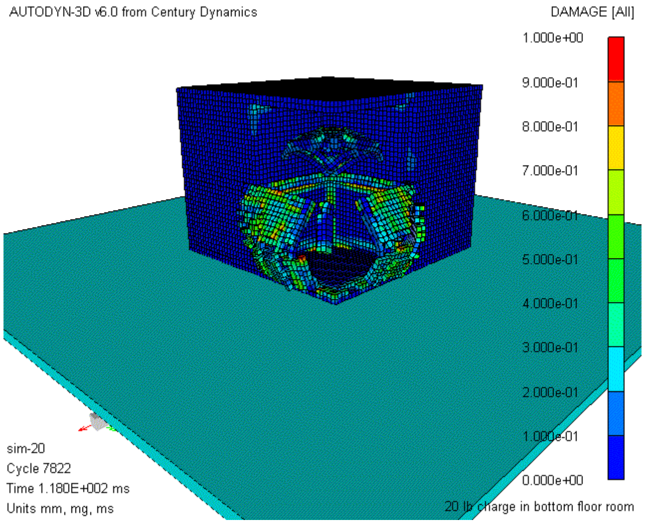
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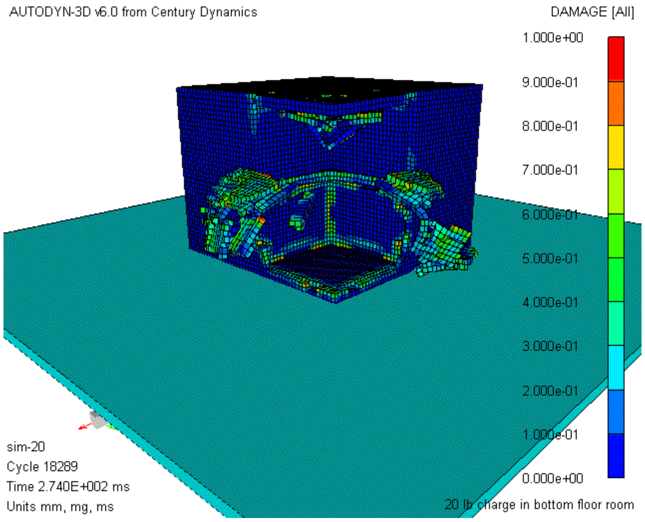
20 lb charge in bottom floor room

3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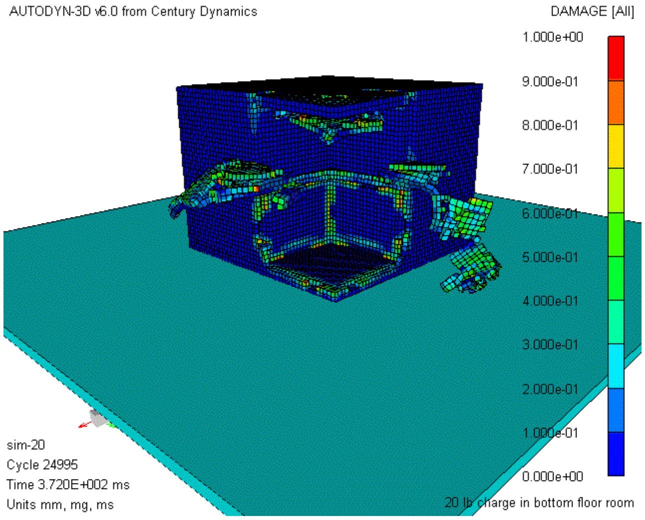
4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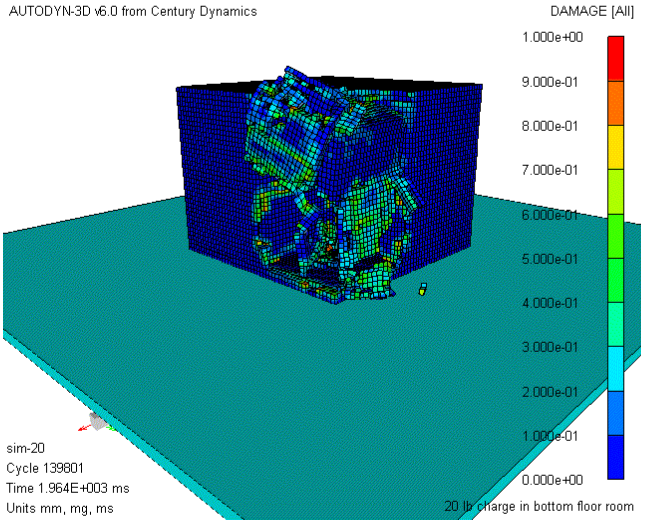
20 lb charge in bottom floor room

5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6

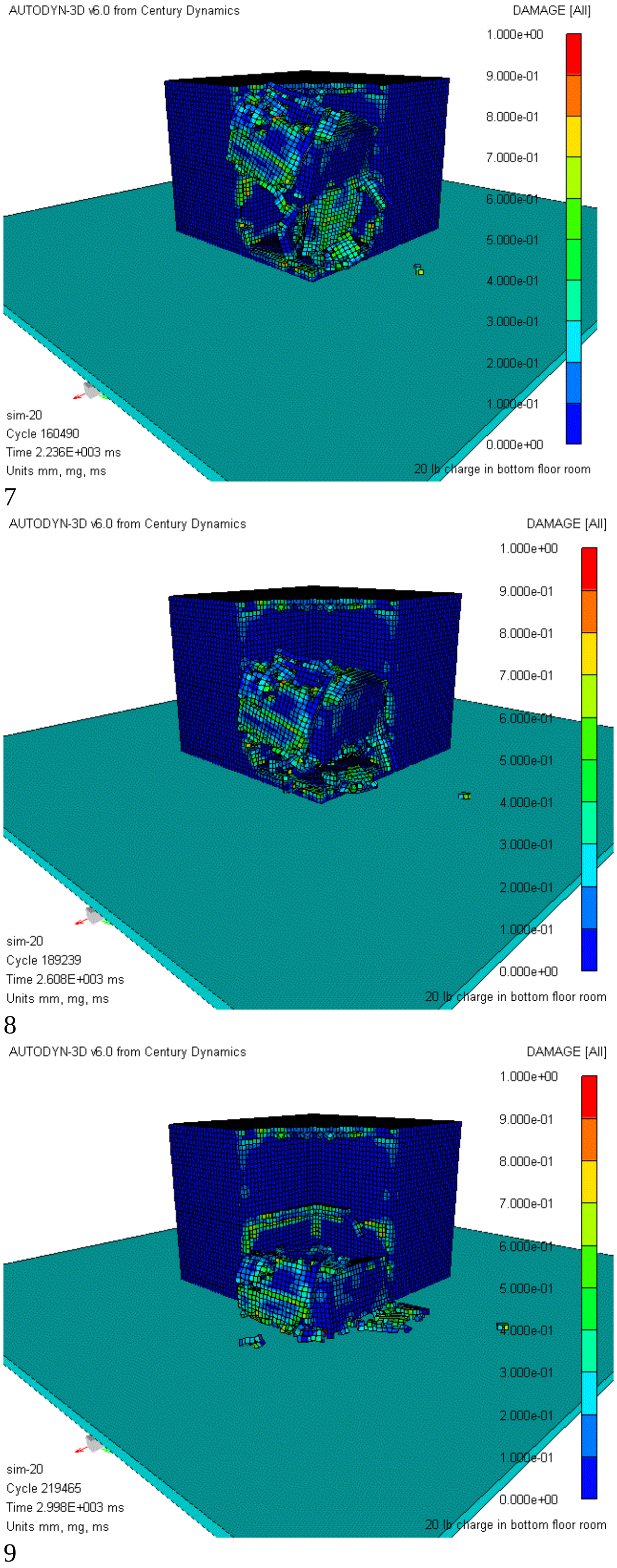

Fig. 7 SIM 20 20lb TNT Charge Within a Multi-Room Building. The frame sequence begins with 1 and progresses to 9 with sequence number noted at lower left.

While results from SIM 20 shown in Figure 7 seem appropriate, they need to be experimentally validated. There is potential for creating robust models of many types of building configurations and building materials; however, there must be a solid backing of experimental data before the models can be completely validated. Scaled testing of building configurations and materials will be imperative to furthering this modeling technology. Variables that still exist for study include the effects of construction jointing between walls and ceilings, walls and foundations, and walls and other walls. The material properties of the concrete could also be studied in more depth to create more accurate depictions of the fragments created by the blast. Currently the model is considering the concrete as uniform and without reinforcement, and with seamless joints. This is hardly a depiction of current construction practices, and should be explored in future studies.

Throughout the model development, a major goal was to determine the size of charge necessary to completely reduce the room in the model to rubble, and subsequently feature this room in a larger model of a multistory, multi-room building. Through multiple iterations using varying charge sizes, grid sizes, and increasingly robust AUTODYN settings, a 20lb. TNT charge was found to effectively destroy the single room, while not throwing fragments thousands of feet. In reality, the optimum charge size for destroying a single room in this model lies somewhere between 10 and 20 lbs; however, since 20 lbs provided appropriate results, refinement of this value was not necessary. In addition, this charge size fits nicely into the upper range of weapon systems to be considered by the AmmoSIM System.

## CONCLUSIONS

The numerical model described in this paper was a support portion for a larger project to assemble a diagnostic tool for soldiers in the field. By defining goals and assumptions for the model, results were achieved with minimal computational cost. In other words, the models were able to run through their entire cycle in an acceptable timeframe of less than a few days.

The ability to couple Euler air grids with Lagrange walls and fill parts for solid surfaces (ground) allowed for complex models to be developed that weren't possible just a few years ago. AUTODYN allows for the user to couple the grids within the graphical user interface without the use of user defined subroutines. These features allowed for focus on manipulation of the material properties as well. Material properties associated with the RHT concrete model showed reasonable results in the final simulations of this project. An expected breakage pattern was apparent once a proper strain erosion rate was applied.

Through several simulations, a TNT charge size of 20lb was deemed appropriate for the complete destruction of one of the monolithic concrete rooms without dispersing fragments for a large radius. Once the single room was successfully modeled, it was featured in a multi-room, multi-floor situation. The results from the model look promising; nevertheless, scaled testing could validate the model as well as provide invaluable data for future models.

With future projects, it is hoped that the scope of work for the models can be expanded and validated through a minimum of scaled testing. Empirical data is necessary for furthering the development of this numerical model as well as the analytical models that accompanied it in the AmmoSIM project.

## ACKNOWLEDGEMENTS

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