

ASSESSMENT OF BLAST LOAD PREDICTION IN AN URBAN ENVIRONMENT

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Abstract

The development of blast mitigation methods and the design of structural retrofits depend heavily on the ability to accurately model blast propagation in an urban environment. The Combating Terrorism Technical Support Office (CTTSO) and the Department of Homeland Security (DHS) Science and Technology Directorate (S&T) are evaluating blast prediction methods through a combined program of half- to full- scale tests of simulated urban environments and the application and assessment of state-of-the-art numerical modeling. The ongoing, multi-year test effort is being performed by the Energetic Materials Research and Test Center (EMRTC). Protection Engineering Consultants (PEC) is managing and directing the numerical modeling component of this program, using a team of highly capable and well qualified organizations, which develop and apply their own computational fluid dynamics (CFD) codes. The data analysis techniques being applied to this challenging program and the significant findings to date will be presented in this paper.

Key words: Blast – Modeling – Urban – Structures – Tests

1. Objective

The objective of the work being conducted by Protection Engineering Consultants (PEC) for the Combating Terrorism Technical Support Office (CTTSO) and the Department of Homeland Security (DHS) Science and Technology Directorate (S&T) is to utilize the large database being developed by the Energetic Materials Research and Test Center (EMRTC) to evaluate the accuracy of existing CFD codes to predict overpressure in an urban environment. This paper will summarize the data analysis methods being used and the comparison results for several scenarios tested to date. Two modelers are currently using their CFD codes to analyze selected urban environment and charge configurations to develop pressure histories at locations corresponding to actual gauge locations from the EMRTC tests. Options for additional modelers' participation may be implemented in the future.

PEC has analyzed predictions from Applied Research Associates (ARA) using their Second Order Hydrodynamic Automatic Mesh Refinement (SHAMRC) code and from SAIC using their Finite Element (Navier Stokes) Flow Solver (FEFLO) code. Six unique scenarios have been compared to test results thus far. All six scenarios are for conventional cylindrical and spherical C4 explosive charges at two different heights of burst and at varying locations within the urban canyon test facility.

As the first step in the effort, PEC has established the metrics to be used to compare the analytical predictions to the experimental data. An extensive study of many possible statistical metrics helped PEC determine which ones would provide CTTSO, DHS, and the modelers the most useful indication of how well each code is performing. PEC is responsible for acquiring and organizing the experimental and analytical data, assessing the performance of each predictive code using the established metrics, and creating a controlled repository for developed and derived data. This approach has resulted in: 1) a consistent application of all data analysis and evaluation procedures, and, 2) an unbiased assessment of the predictive code performance.

2. Testing

The goal of the testing at EMRTC was to generate high quality pressure histories within a simulated urban environment, using conventional and non-conventional explosives. Only the conventional C4 explosives data is being used for this program. The environment was created and shaped by positioning and stacking non-responding reinforced concrete test modules on a flat concrete surface. The test modules contain many flush-mounted pressure sensors and have been designed to withstand a specific charge weight and standoff distance.

The building layouts and environment scenarios have been designed such that different aspects of blast propagation can be explored in detail. The key parameters are the height, depth and width of individual buildings, the distance between multiple buildings, the variations in height of buildings, and the orientation of buildings to the charge. The test layouts are shown in Figure 1. One charge location was used for the straight street configuration, at two heights of burst (HOB). Six separate charge locations have been used with the enhanced open square layout. Overall, the site layouts and gauge locations were chosen to provide multiple examples of diffraction, reflection, and diffusion of the blast wave.

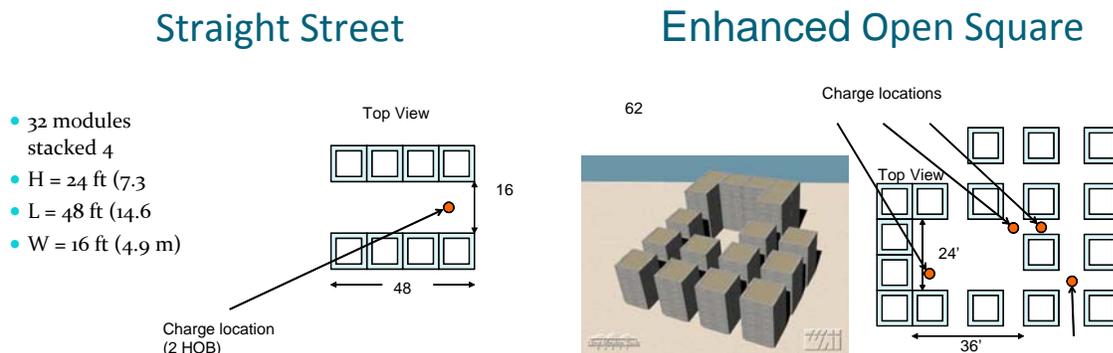


Figure 1. Urban Environment Test Configurations (Stanley and Abernathy 2011)

EMRTC has performed 43 tests in a straight street configuration and 50 tests in an enhanced open square configuration (Stanley and Abernathy 2011). Figure 2 shows the setup for one of the straight street shots conducted at EMRTC. An enhanced open square test setup is depicted in Figure 3.



Figure 2. Straight Street Urban Environment Test Setup (Stanley and Abernathy 2011)



Figure 3. Enhanced Open Square Urban Environment Test Setup (Stanley and Abernathy 2011)

In the current effort, numerical analyses of up to 10 unique tests using conventional cylindrical and spherical C4 charges are being performed by the modelers to assess the capabilities of the CFD codes. The data from the remaining tests may be held in reserve, to be released in the future and to serve as validation for later improvements and modifications of the numerical codes. If the decision is made to withhold some of the data at the end of this program, data from the reserve tests will permit modelers to try fresh blind predictions after future improvements to their codes have been made. The emphasis here is on enhancing the confidence of the modeling capabilities in the future.

3. Numerical Analysis

Physical tests have been performed at EMRTC before the corresponding numerical analyses are executed. Thus, the modelers are able to use the most accurate information regarding initial conditions (weather, setup, charge configuration) for creating their models. The test *results* are initially withheld from the modelers to prevent artificial prediction adjustment, ensuring that all predictions are performed blind. The limited release of test data to the modelers following their analyses is being determined by CTTSO and DHS S&T.

For each analysis, the numerical modelers provide their pressure history predictions in DPLOT format. They also analyze their data to report specified metrics to PEC in spreadsheet format. Five key metrics are being studied in detail:

- Time of arrival
- Peak pressure
- Time of peak pressure
- Maximum impulse
- Time of maximum impulse

For consistency, PEC has provided guidelines for picking these metrics (as illustrated in Figure 4), a format for naming the files, and a spreadsheet template designed for automated data importing during the PEC analysis. PEC also reviews samples of the predicted pressure histories and reported metrics to ensure that the modelers are being consistent in data extraction.

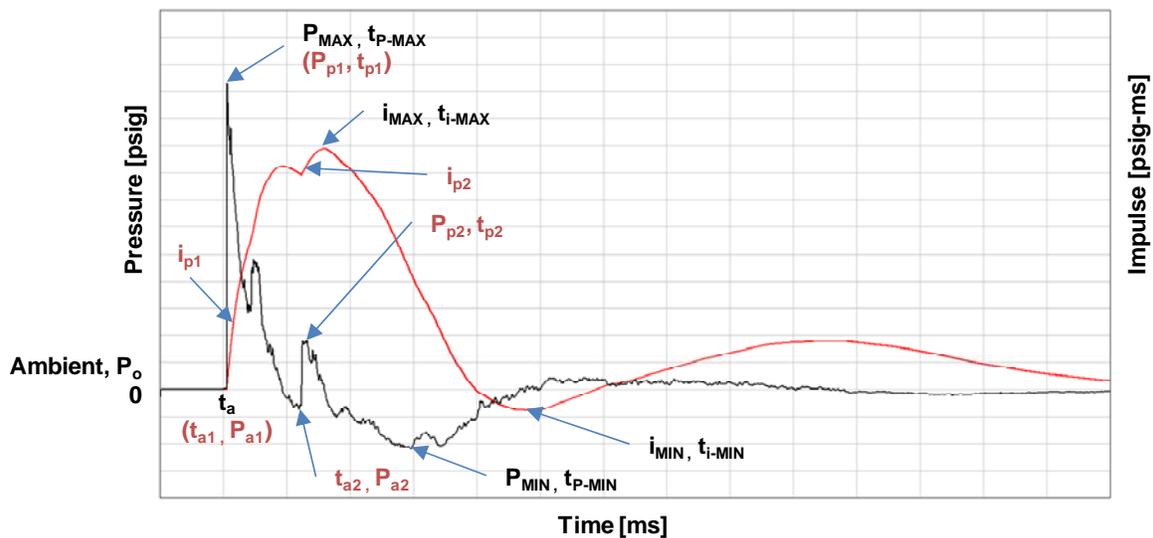


Figure 4. Guidelines for Selection of Key Metrics

4. Data Analysis and Code Evaluation

A large amount of data is being collected during each test, with up to 75 pressure gauges being used. Each test configuration is repeated three times to ensure consistent results. Even with only 10 test configurations, the resultant data set is quite large since it contains all measured pressure histories for each set of three repeat tests, corresponding predicted pressure histories by each modeler, and metrics determined for the measured and predicted pressure traces. Thus, data analysis required a carefully structured plan.

Since each test scenario (including layout and charge configuration) is repeated three times, PEC determined a suitable method of “averaging” results. This allows a reasonable comparison of modelers’ pressure histories with experimental pressure histories. To facilitate pressure history comparison, macros were developed to search for pressure peaks and associated times of arrival to determine the desired metrics from the experimental results. The resultant values for the selected key metrics are then compared to predicted values for each gauge location in each test.

Multiple statistical parameters were originally studied to determine the parameters best suited for reporting comparison results to CTTSO and S&T, and separately to each modeler. PEC considered using a variety of parameters, including: percent error, absolute percent error, standard Z-score, normalized percentage based on Z-score, count of positive percent error, and percent passing a 90% confidence level. The percent error between a predicted metric and the average of that metric for the three repeated tests indicates the degree to which the metric is being under- or over-predicted. The absolute percent error reflects the overall accuracy of a given metric. The standard Z-score and the normalized percentage based on Z-score bring the repeatability of the tests into play since they involve the standard deviation of the metrics between the three repeated tests. The count of positive percent error gives an indication of conservatism of results by revealing the number of instances of over-predicted metrics. The percent passing a 90% confidence level reveals the degree to which the metrics fall within a 90% confidence interval of a normal distribution. All of these measures were used for the first few scenarios, but it was later determined that the percent error and absolute percent error provided the most beneficial information to the Government and to the individual modelers.

Statistical analysis was performed for the five key metrics at each gauge location and by region based on scaled standoff for the straight street scenarios or geometric location for the enhanced open square configurations. The region results are reported to the modelers. There are two motivations for using regions: (1) it makes the overwhelming amount of data more manageable for reporting to CTTSO and DHS, and (2) it allows PEC to provide performance feedback to the modelers without divulging individual pressure histories. For straight street cases, the 25 gauge locations are grouped into three regions by scaled standoff distance, z , from the charge: near-field ($z < 3 \text{ ft/lb}^{1/3}$), mid-field ($3 \text{ ft/lb}^{1/3} \leq z \leq 7 \text{ ft/lb}^{1/3}$), and far-field ($z > 7 \text{ ft/lb}^{1/3}$). For the enhanced open square configurations, the regions were defined based on geometric location in relation to the charge. An example of the regions defined for charge location 1 for the enhanced open square is depicted in Figure 5.

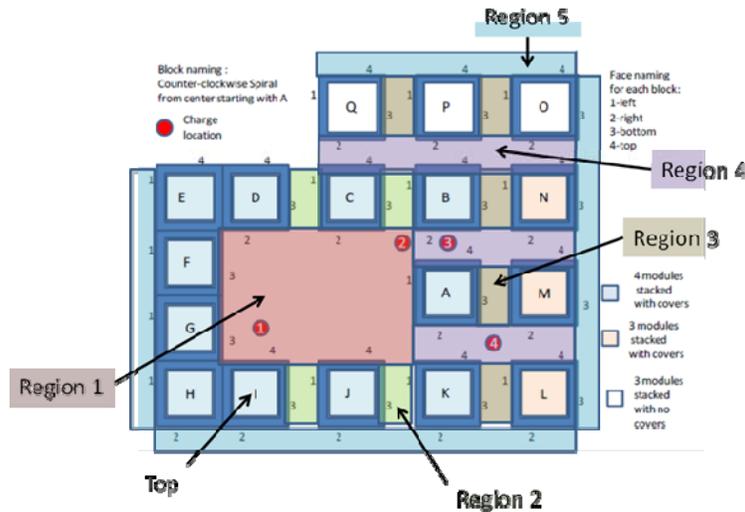


Figure 5. Example of Region Definitions for Charge Location 1 of the Enhanced Open Square

Figure 6 illustrates percent error for several key metrics for a single code. This particular example is for a straight street scenario (Figure 2), and the regions are based on scaled standoff distance from the charge. Region 1 would be considered near-field, with Region 3 representing gauge locations furthest from the charge. A variety of such charts are developed for each code and each test scenario, representing other statistics.

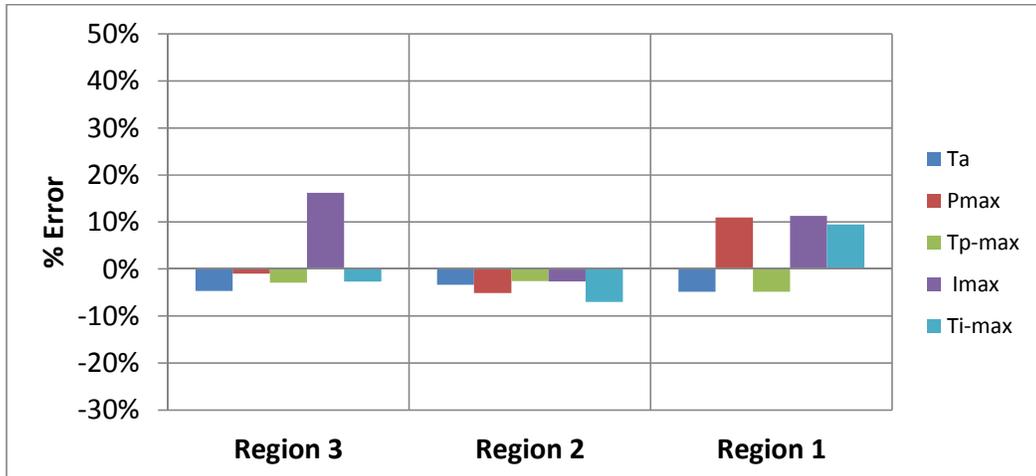


Figure 6. Dynamically Linked Pivot Chart Showing Metric % Error for One Code

Another measure of a code's performance is derived using profile comparison methods for the pressure and impulse history curves. The predicted pressure history at each gauge location is compared to the average of the three tests repeated for a given scenario. This exercise provides information about how well the shape of the predicted curve matches measured pressure histories. Example profile comparisons for pressure and impulse are illustrated in Figure 7, where the red

curves represent predicted values and the black curves are averaged test data. The green shadowing represents two standard deviations of variance.

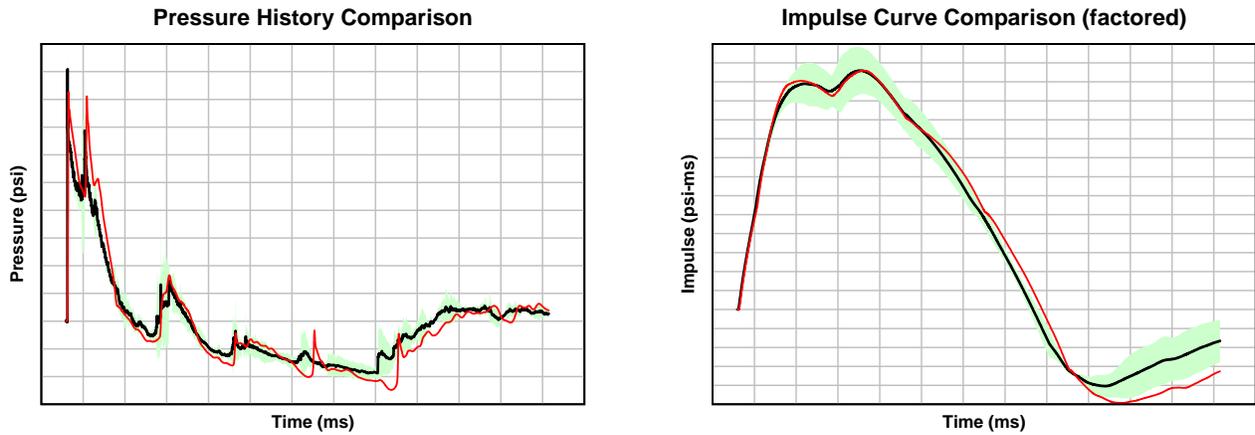


Figure 7. Sample Profile Comparisons for Pressure and Impulse

During the curve profile analysis, the percentage of points on the curve that fall below, are within, or are above two standard deviations are recorded and are ultimately used in the scoring of each code. Again, this profile information is reported per geometric region, as shown in Figure 8, and a root mean square error is reported as well.

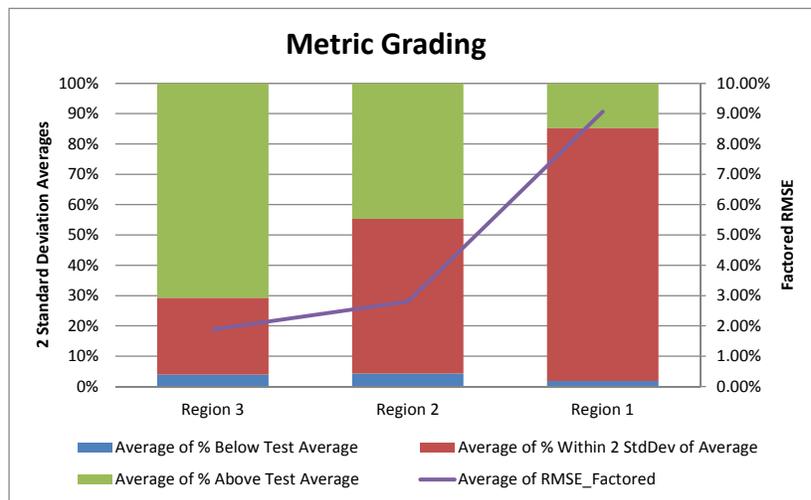


Figure 8. Profile Comparison Grading

4.1. Code Evaluation Results for Straight Street

Code assessments have been made for four straight street scenarios for ARA’s SHAMRC and SAIC’s FEFLO analyses. The overall percent errors for all three regions and for all four scenarios are given in Figure 9. There is generally good agreement for the five key metrics. Based on impulse (most significant metric in terms of structural response), the percent errors can be considered very good for SHAMRC and reasonable for FEFLO for the straight street scenarios.

Figure 10 provides a similar comparison for both codes for the absolute errors of the key metrics. Over all four straight street scenarios, both codes performed adequately over all gauge locations, but SHAMRC performed best in predicting the peak pressure and impulse. Most variation was observed in the near-field region with notable variations between gauges, scenarios, and regions.

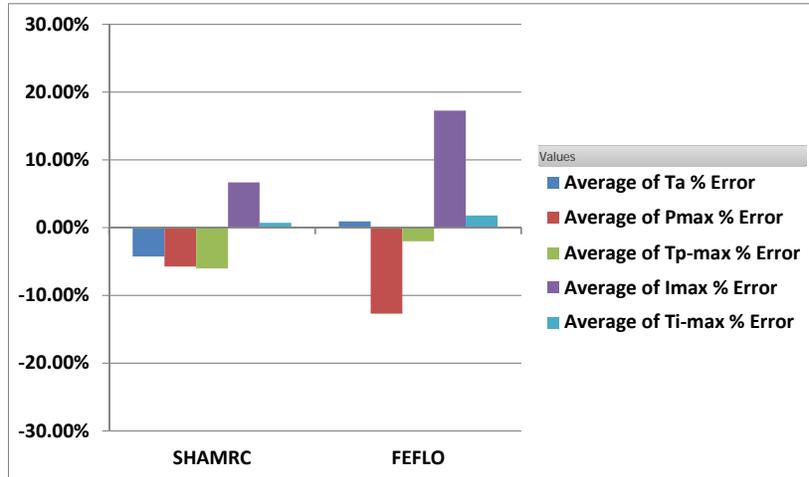


Figure 9. Overall Straight Street Percent Errors for SHAMRC and FEFLO

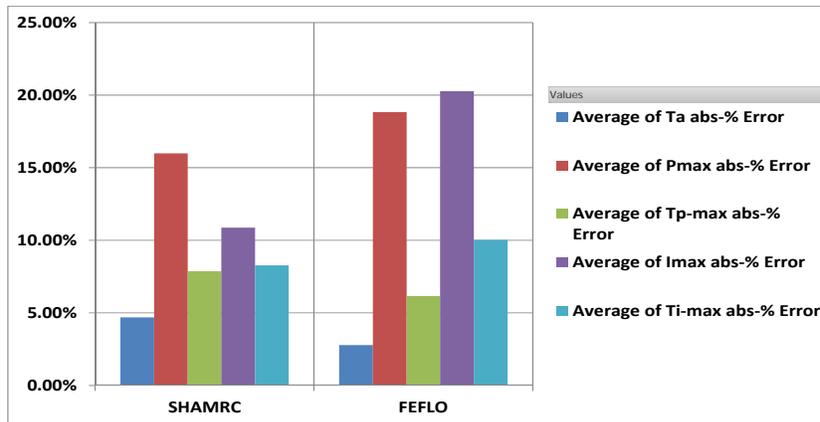


Figure 10. Overall Straight Street Absolute Percent Errors for SHAMRC and FEFLO

Example results of the profile comparisons for both codes for one straight street configuration are shown in Figure 11.

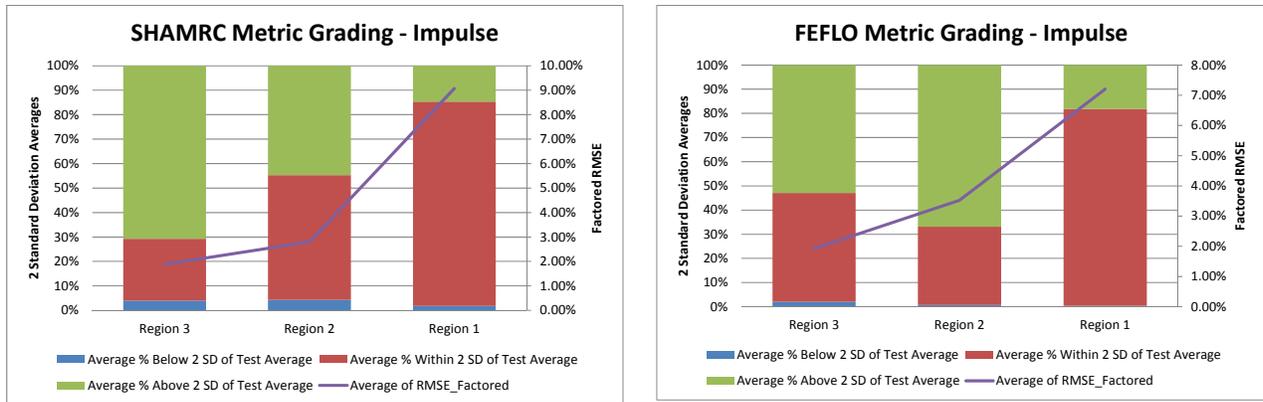


Figure 11. Example Profile Comparison Results

4.2. Code Evaluation Results for Open Square

Two open square scenarios have been analyzed for ARA’s SHAMRC and SAIC’s FEFLO predictions. The two open square scenarios include different charge sizes at different charge locations. Example overall results are given for the scenario at charge location 1 with the regions defined in Figure 5. The percent error and absolute percent error comparisons over all regions for this open square scenario are shown in Figure 12 and Figure 13.

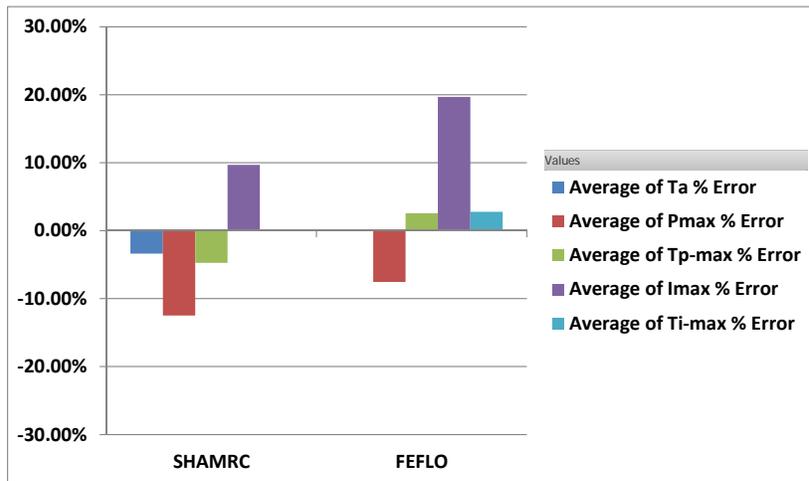


Figure 12. Overall Open Square Percent Errors for SHAMRC and FEFLO for Charge Location 1

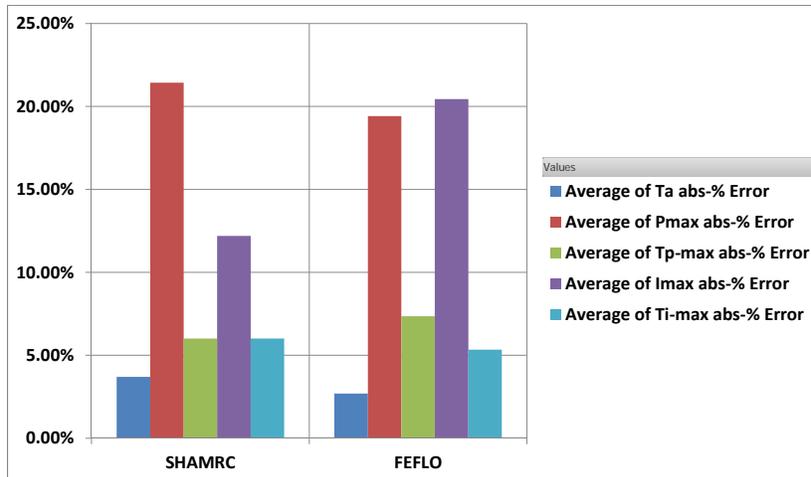


Figure 13. Overall Open Square Absolute Percent Errors for SHAMRC and FEFLO for Charge Location 1

5. Summary of Observations and Lessons Learned

For the straight street scenarios, SHAMRC predicted peak pressure and impulse better than FEFLO. Most variation for both codes was observed in regions near the charge. The open square evaluations show that absolute percent errors for peak pressure are slightly lower for FEFLO over the six regions. The absolute percent errors for maximum impulse are generally lower for SHAMRC. Each of the time metrics (time of arrival, time of peak pressure, and time of maximum impulse) were predicted well by both codes.

It should be noted that some pressure histories at individual gauge locations were less consistent between the three repeated tests. This certainly affects the averages and standard deviations of the test metrics being compared to the predicted metrics. PEC addressed this issue throughout the analyses by either ignoring one of the three repeated tests or eliminating a gauge from the comparison if it exhibited poor agreement between tests. It is also important to note that pressure is more difficult to predict for some gauge locations with multiple reflections, diffraction, or deflections. The effect of problematic gauges was minimized by reporting the results by region, as well as by individual locations.

Finally, a comparison is being made of the amount of CPU and clock time required to run each code for each scenario. The CPU time for the SHAMRC runs was dramatically more than for the FEFLO runs. The increased CPU time may result in better accuracy, but the question arises, “is it worth the extra time?” It is important to quantify the amount of error that is acceptable for modeling in urban scenarios. Criteria should be developed to define the appropriate level of accuracy required for the blast design community and for first responders. The existing modeling results from SHAMRC and FEFLO can then be evaluated using these criteria.

6. Effects of Modeling Accuracy

The comparison of experimental data with numerical predictions from all codes analyzed will identify opportunities for CFD code improvements. Since fast-running models (FRMs) are often derived from results produced by CFD codes, the implication to the FRMs is important as well. If the CFD models need improvement, this will be amplified when the results are applied to lower resolution FRMs.

In addition to improving the current CFD codes, another goal is to develop appropriate and required accuracy criteria for blast propagation predictions for the blast design community and first responders. Accurate predictions of blast propagation are critical in determining structural response and potential casualties. The impact of uncertain levels of accuracy can greatly affect the required standoff for structural components to prevent severe damage or collapse. Thus, analysis should be performed for common structural component types to explore the effects of load deviations on the level of protection as defined by the US Army Corps of Engineers (COE) and GSA response limits (PDC TR06-08 and GSA PBS-PB100). A load sensitivity analysis on evacuation distances required for first responders should then be performed relative to human injury due to blast or blast-induced debris, taking into account the effects of the urban setting. The load sensitivity results for structural damage and evacuation distance requirements can then be compared to the geometric regions being used in the error analysis of the CFD modeled results in this study. Based on these results, it will be possible to assess how much the urban terrain increases the need for modeling accuracy. The load sensitivity results applied to the urban terrain data will show how blast prediction inaccuracy can lead to over- or under-design of close-in and distant structures, as well as lead to either excessive or else unsafe standoff perimeters for bomb technicians and first responders.

7. Conclusions

Since explosive devices will continue to be a preferred terrorist tactic, having confidence in using modeled results is paramount for engineers, architects, counter-terrorism experts, city planners, and the military, all of whom need to be able to predict blast loads within an urban environment within acceptable error tolerances. The predicted loads will be used to design buildings, develop blast mitigation methods and retrofits, route and restrict vehicle traffic, and plan for evacuations when a bomb threat is presented. The prediction of these loads has been, and will continue to be, challenging. However, a huge step toward meeting this challenge is in progress. Comparison of the modeling predictions to the voluminous, high-quality, experimental data and assessment of these predictions using developed accuracy criteria will enable a true evaluation of existing and future numerical codes for predicting blast in an urban environment.

8. Acknowledgement

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