



A 28 TEAM ROUND ROBIN CONCRET SLAB IMPACT & PERFORATION EFFORT: IMPLICATIONS FOR VALIDATION?

Leonard E Schwer

Owner, Schwer Engineering & Consulting Services, Windsor, CA USA (Len@Schwer.net)

ABSTRACT

The term Round Robin is sometimes used to describe the process of assessing a group's ability to compute solutions for a particular class of physics or an application area.

Round Robins are typically performed in conjunction with comparative experiments. While more costly, Round Robins that include comparative experiments have the potential advantage of validating some of the group's computational models – although no guarantee is implied.

In addition to the cost of conducting quality laboratory experiments, there is an additional, somewhat hidden, cost of appropriate planning. Poorly planned Round Robins, even if the experimental results are of high quality, can result in low confidence in a subsequent validation assessment of the models, e.g. if the description of an experiment was incomplete or the if data collected do not permit adequate validation.

In the subject concrete slab impact Round Robin, there were three impact problems defined. One was of historical interest from the so called Meppen test series, and two were purpose built experiments. Each of the purpose built experiments was repeated and the results concealed from the calculators, i.e. blind predictions were made by the calculators.

There were 28 participants in the computational portion of the Round Robin, but not all participants provided results for all three problem definitions. In general, the simulation results exhibited a large amount of variability, as might be expected when the problem statements did not provide adequate specifics, and a wide range of modeling approaches were used by the participants from simple engineering models to so called first principles models.

In this manuscript, some of the aspects of planning and executing a successful Round Robin are offered for consideration, using examples of things that can, and unfortunately did, gone wrong in this Round Robin.

INTRODUCTION

The Committee on the Safety of Nuclear Installations (CNSI) issued a final report¹ in early 2012 entitled:

“Report on Improving Robustness Assessment Methodologies for Structures Impacted by Missiles IRIS 2010”

The Committee on the Safety of Nuclear Installations (CNSI) operates under the jurisdiction of the Nuclear Energy Agency (NEA) established on 1 February 1958. The NEA in turn operates under the Organization for Economic Co-Operation and Development (OECD) a unique forum where the governments of 34 democracies work together to address the economic, social and environmental challenges of globalization.

The report documents the main results and conclusions of the benchmark study launched in February 2010. The study included the participation of twenty eight teams from twenty different organizations from eleven countries that concluded in December 2010 with a final workshop convened to

¹ The report is currently restricted to CNSI members <http://www.oecd-nea.org/nsd/docs/indexcsni.html>

discuss the simulation results. Several related presentations, and a workshop, were conducted at the November 2011 Structural Mechanics in Reactor Technology - SMiRT 21 Conference (<https://smirt21.hbni.ac.in/>), see the proceedings of the SMiRT Conference.

The purpose of the benchmark activity was to

“... conduct a round robin study, called IRIS_2010 [Improving Robustness assessment of structures Impacted by missileS], where the different computer codes, modeling approaches methods and results were to be compared to data and other codes used to determine effective means of analyzing the structural and vibrational effects of a postulated missiles impact on a NPP [Nuclear Power Plant].”

The benchmark organizing committee specified three categorizes of concrete slab impact experiments to be simulated:

1. Test Meppen II-4 is one of the series of tests performed during the 1980s at Meppen, Germany and whose results are well known and interpreted through numerous papers; see for example the past proceedings of SMiRT conferences.
2. A dedicated test series of bending mode failure with repeated tests.
3. A dedicated test series of punching mode (perforation) failure with repeated tests.

The logic for selecting these tests was to first allow participants to calibrate their modeling approach to the known results from the Meppen test, i.e. demonstrate they could successfully model a concrete impact scenario. Based on the assumed success of the Meppen test simulation, participants were to predict the results of similar concrete slab impact tests where the slabs were impacted in a manner that produced significant bending induced damage, but no perforation, nor even significant penetration. These bending mode tests, and the next series of perforation tests, were purpose built experiments whose results were withheld from the participants until after the predictions were submitted to the organizing committee, i.e. so called blind predictions.

Not all 28 participants provided results for all three test categories. Further, although the organizing committee did an exceptional job of specifying the desired simulation results, to include providing reporting Microsoft Excel file templates, several participants failed to complete the reporting templates, and inevitably errors were made in entering data into the templates.

The present manuscript is focused on the organization and execution of the Round Robin, i.e. lessons learned which hopefully will benefit other Round Robin organizers. Various lessons are illustrated using events that occurred during the Round Robin with a focus on those related to the blind prediction of the concrete slab perforation tests. Simulating perforation is a much more challenging numerical modeling task than simulating impacts that do not include significant target penetration. Also, when the structure of concern is a nuclear power plant, failure to predict impact damage can be a serious problem, but failure to predict a credible penetration threat can be catastrophic.

PERFORATION TEST DESCRIPTION

Figure 1 shows half of a quarter symmetric model representing the initial configuration of the perforation (punching) test. The square concrete slab is 2.1 m on a side and 0.25 m thick with a layer of 10 mm diameter reinforcement near the top and bottom surfaces. The slab is restrained on all four sides with a fairly complex fixture that is likely to act somewhere between simply supported and clamped. The concrete unconfined compressive strength was 67 MPa, based on cubical specimen testing.

The projectile is a steel pipe of radius to thickness ratio of 8.4 with a solid steel hemispherical nose. The steel pipe is filled with concrete to increase the total mass to 47 Kg and impacts normal to the slab at a nominal 135 m/s. Three such slabs and projectiles were constructed and tested with quite similar responses.

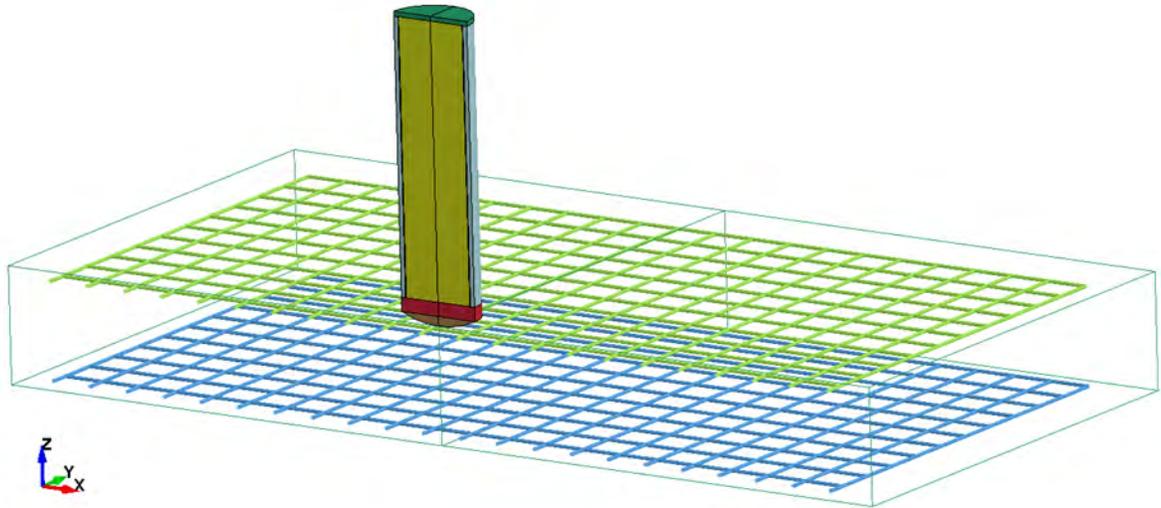


Figure 1 Half of quarter symmetric penetration model illustrating reinforcement, projectile and concrete slab in outline.

The requested results reporting were quite extensive and could be divided into three main categories:

1. Material Characterizations – Describe the material modeling for the three main test components:
 - Concrete
 - Missile
 - Reinforcement
2. Missile Results –
 - Impact duration
 - Maximum force
 - Impulse
 - Deformation
3. Target Results –
 - Concrete slab displacements
 - Reinforcement strains
 - Cracking
 - Front ejecta
 - Rear spall

VARIABILITY IN THE NUMERICAL RESULTS

Among the CNSI report's conclusions was this statement about the experimental and numerical results:

“It was found that simulation scattering is large while tests scattering were rather small. Analyst's assumptions and choices are the main origin of the scattering. Simulations were found to be not only software dependent but analyst dependent.”

This conclusion, about the variability in the numerical results, should not come as a surprise to anyone that has been involved in Round Robin exercises.

A generalization of the analyst's task is to solve an initial boundary value problem – as this is precisely what general purpose numerical algorithms, e.g. finite element codes, are designed to do; but too often 'disguised' behind a graphical user interface. The key task of the organizing committee is to

sufficiently describe the initial and boundary conditions, and materials such that the analysts' options and choice are minimized. Image defining an X-Y-Z point in space and asking analysts to create a straight line through this points – the possibilities are infinite.

For a relatively complex problem definition, as in the case of reinforced concrete slab perforation, the list of items needing specification is quite large. In the next two subsections, some of the key specifications that were omitted are described.

Concrete Specification

For all three types of impact experiments, the organizers clearly specified the concrete unconfined compressive strength. For the average civil engineer, and most if not all the organizers are civil engineers, this completely specifies the concrete. Such a concrete description is adequate if you are designing a structure whose stresses are intended to remain below the unconfined compressive strength, i.e. a typical safe civilian structure design. However, the purpose built impact experiments were not designed as such safe structures. Just the opposite, these structures were to be tested such that significant damage, and even slab perforation, would occur.

The necessary concrete specification for the purpose built slabs should have included a description of the shear failure surface and the compressibility of the concrete, i.e. the pressure versus volume strain. Figure 2 attempts to illustrate the role of the shear failure surface in such impact experiments and the inadequacy of only specifying the unconfined compression strength. In this figure a 29.7 MPa unconfined compressive strength concrete is indicated by the gold colored circle in the lower left of the stress difference versus mean stress diagram. For this unconfined compressive strength, the corresponding shear failure surfaces for four concrete models are shown. These LS-DYNA concrete models use only the unconfined compressive strength to internally generate the illustrated shear failure surfaces.

Let us assume the impacted concrete slabs generate a mean stress under the projectile of 150 MPa. Under this assumption, the modeled strength of the concrete could vary from about 75 MPa for MAT016 to 250 MPa for MAT072R3 – a factor of more than three in strength. Since no shear failure data was provided for the concrete used in the experiments, every concrete model selected by the calculators likely had a quite different shear strength envelope.

In addition to failing to adequately specify the concrete shear failure envelope, the organizers also failed to specify the concrete compressibility. Since all concrete models require specification of the pressure versus volume strain response, even if it is simply the elastic bulk modulus, this important concrete response was also left up to each calculator to specify.

Given the organizers did not fully specify the concrete properties, it would be reasonable to assume that all the calculators at least used the specified unconfined compressive strength. The organizers provided in the reporting templates a place to list the unconfined compressive strength used in for each of the three impact tests simulations. Examining these reported unconfined compressive strengths provides another lesson.

For one of the purpose built experiments, the organizers clearly specified the concrete unconfined compressive strength as 65 MPa from 150 mm cubical samples and 61 MPa from 150 mm cylindrical samples. These two strength values are illustrated by the dashed lines in the left most image of Figure 3. The triangular symbols indicate the calculator reported unconfined compressive strengths; the abscissa is just a number assigned to each of the participating calculators. The image on the right of Figure 3 shows a histogram of the distribution of unconfined compressive strengths with an interval size of 4 or 5 MPa.

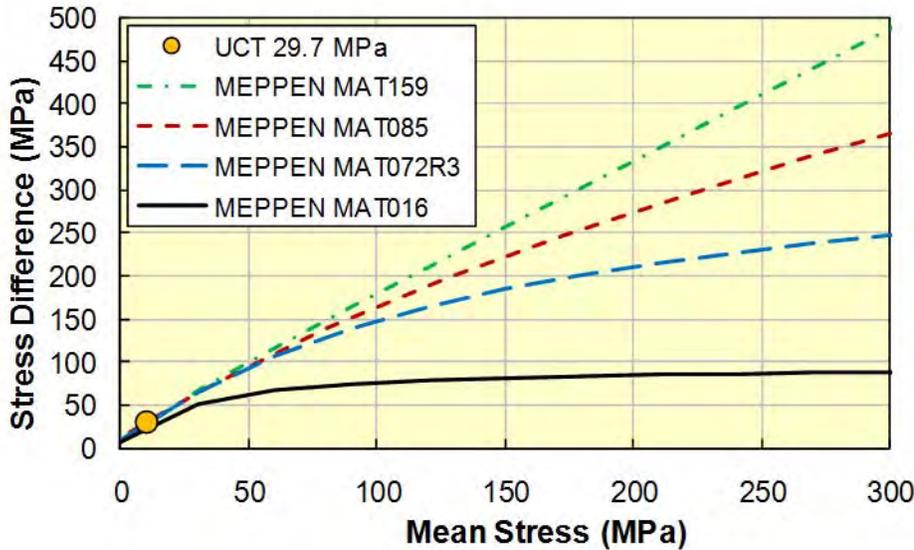


Figure 1 Illustration of a 29.7 MPa unconfined compression strength concrete and four option shear strength surfaces.

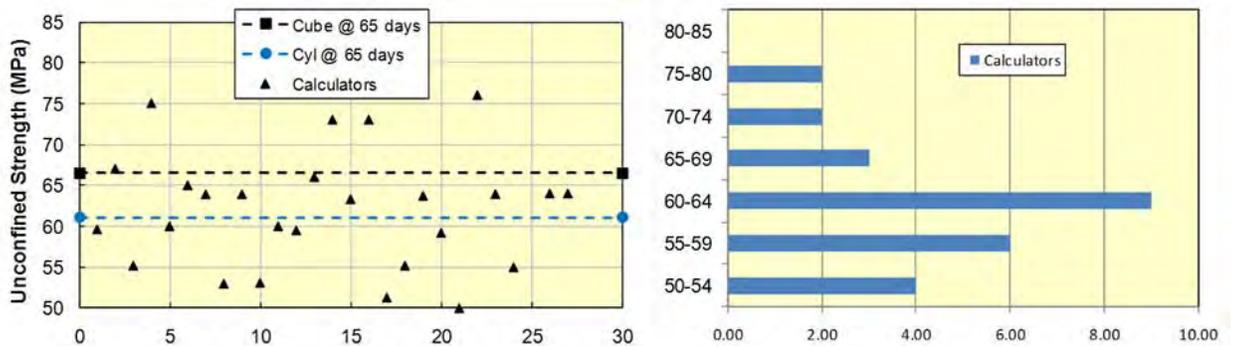


Figure 3 Distribution of reported unconfined compressive strengths for one of the benchmark concrete slabs.

The maximum reported unconfined compressive strength was 76 MPa and the minimum was 50 MPa. Whatever the reason for using such extreme values, the lesson here is that differences between prescribed values and those used in a Round Robin should be discovered before the blind predictions are submitted. It is suggested that had there been a meeting of the calculators to present and discuss their preliminary predictions, before the experimental results were made know, many if not most of the outlying strength values could have been identified and rectified. Such preliminary presentations are quite successful in eliminating not only blunders, but misinterpretation of the experimental specifications with a resulting reduction in the variability of the final predictions.

Projectile Strain Rate Specification

The projectiles used in the concrete slab bending mode failure experiments were thin walled (2 mm) stainless steel with material designation EN 1.1443. Although a nominal engineering stress-strain curve was provided for this material, no strain rate data was supplied. This was an oversight because the thin walled stainless steel projectiles buckle and the strain rates in the folds of the buckles are quite high.



Figure 4 Comparison of stainless steel projectile final deformation without (top) and with (bottom) Cowper-Symonds strain rate model.

Figure 4 shows the final buckled configuration of the thin walled projectile model without strain rate effects (upper image) and with the addition of a Cowper-Symonds strain rate model using parameters from the literature. Although the total kinetic energy is the same for both projectiles, the conversion of this kinetic energy into impulse delivered to the concrete slab is different, i.e. without strain rates the impulse is delivered over a longer duration than when strain rates are included. Depending on the response time of the concrete slab, the flexural damage could be quite different for these two cases.

Perforation Test Results Comparisons

The primary experimental measurement for the concrete slab perforation (punching) tests was the projectile residual speed, i.e. the speed of the projectile after it passed through the concrete slab. Calculators were asked to respond to these questions:

1. Did the projectile perforate the concrete slab?
2. What was the exit (residual) speed of the projectile?
3. What was the duration of the penetration, i.e. how long did it take the project to pass through the slab?

Of the 23 teams providing results for the perforation simulation, only seven teams, i.e. about 30%, reported a positive residual projectile speed indicating the slab had been perforated. The remaining sixteen reported a zero or negative (rebound) speed for the projectile². Figure 5 is a histogram illustrating the number of teams that reported projectile residual speeds varying from minus 50 m/s (rebound) to 90 m/s after perforation. The three repeat experiments are closely grouped at about 38 m/s. The largest number reporting a final projectile speed was essentially zero with 11 teams reporting between minus 10 and zero m/s.

Of the seven teams that reported perforation of the concrete slab, only four were within $\pm 20\%$ of the three experiment average residual speed of 38.3 m/s.

² Curiously, some of the zero or negative projectile speed responses indicated the slab had been perforated.

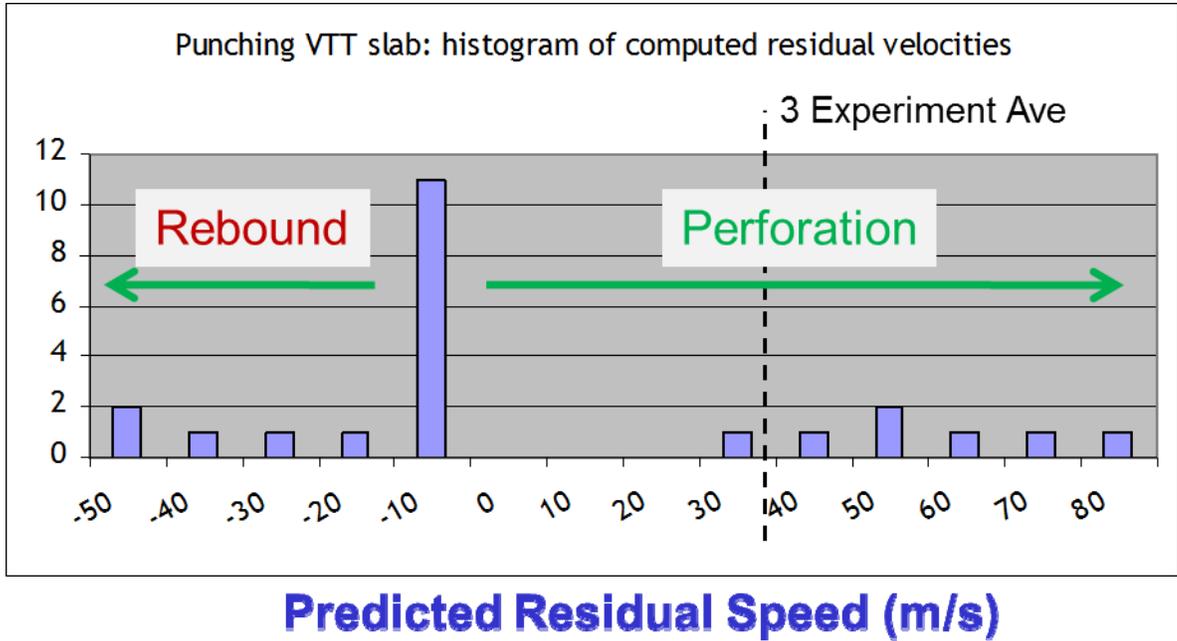


Figure 5 Histogram of predicted residual projectile speed for perforation test simulations.

One way to view the residual speed and perforation duration results is shown in Figure 6 where the residual speed is plotted versus the perforation event duration. One expects some correlation between the exit speed and duration of the perforation event, i.e. the greater the exit speed the shorter the perforation duration and vice versa. The ‘Ideal’ curve shown in Figure 6 is one such possible correlation where a decaying exponential function has been calibrated to the experimental data. As can be seen in the upper left corner, at least two, and possibly four, predictions lie close to this idealized speed-duration curve. While those reporting near zero residual projectile speeds can also be considered ‘close’ to this curve, as their perforation event duration times are meaningless, they were none the less quite far from the experimental exit speed.

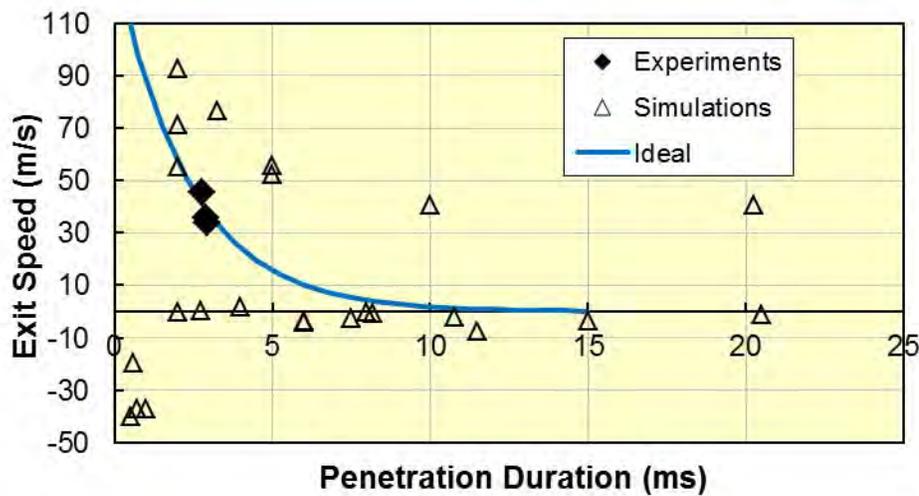


Figure 6 Comparison of experimental and numerical results for projectile exit speed versus perforation duration.

During the final workshop some combined measurement metrics were presented for comparing the experimental and numerical results. While this was an interesting activity, it was performed without considering the weighting of the various items combined in the metric. As an example, the following five results were combined in a proposed metric:

1. Maximal load (average simulation value)
2. Maximal impulse (average simulation value)
3. Duration of impact
4. Maximal displacement
5. Residual displacement

At least the first three of these factors should not be used as part of an accuracy assessment since the first two were not experimental measurements, and the third is related to the unspecified missile material strain rate effects. Those observations aside, the metric used was simply the ratio of the experimental value to the computed value, or its inverse, whichever was greater. The resulting five ratios were then averaged with the implication that a value of unity was a 'perfect' result and large numbers were much less than perfect.

The above is a rather poor example of what should not be termed a metric in a strict mathematical sense as there are well defined characteristics of good metrics. The primary characteristic of a metric is to express 'distance,' e.g. between experimental measurement and the numerical prediction. Although no general guidance exists on how disparate quantities should be weighted in a combined metric, it would appear to be common sense to combine items that are physically related, e.g. projectile residual speed and perforation event duration. To this end the following relative error combined metric was proposed after the workshop:

$$RE_i = \frac{X_{i_sim} - X_{i_exp}}{X_{i_exp}} \quad (1)$$

where RE_i is the relative error between a simulation and experimental quantity. A further advantage of using the relative error is that if no data is reported, as happened all too often in the simulation results reporting, the value of the relative error can be taken as -1, as opposed to the maximum ratio metric which would be infinite. Also, a relative error of +1 indicates the simulation result was double the experimental value.

The proposed replacement metric value is given by

$$V = \frac{1}{N} \sum_{i=1}^N |RE_i| \quad (2)$$

where the absolute value is required to avoid cancellation of positive and negative relative errors. For this form of the metric, the ideal value is zero, and the larger the value the worse the comparison with the data. Figure 7 shows the proposed metric for the same results shown previously in Figure 6, i.e. combining projectile residual speed and perforation event duration. In Figure 7 each reporting team is assigned a number with a corresponding angular position on the 'radar plot' and their combined metric result is plotted as a radius³. As can be easily seen in this figure, only one team's combined metric is within the 50% relative error circle and four other teams are just outside this circle.

³ Not all teams are represented as those with relative error values in excess of unity were omitted.

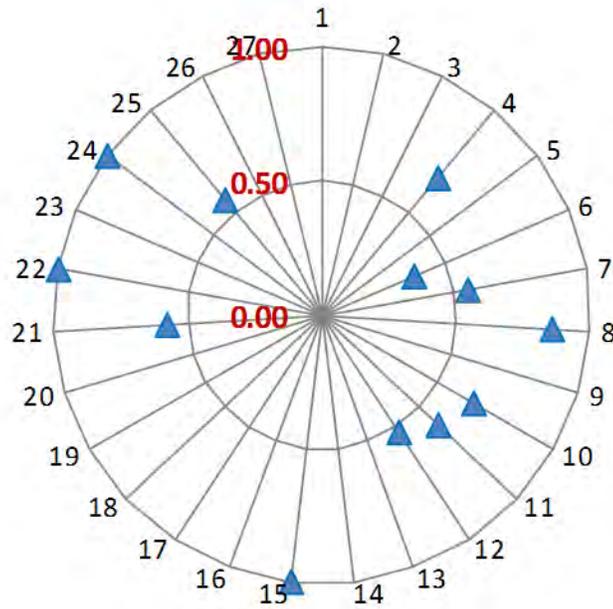


Figure 7 Relative error based metric of performance for the concrete slab punching tests.

SUMMARY AND RECOMMENDATIONS

Some of the errors and omissions attributed to the Round Robin organizers have been identified. While these could be corrected in future Round Robins, there is little reason to hope the predicted results would exhibit greater accuracy and certainly no less scatter. The largest unquantified unknown in all such Round Robins are the abilities of those performing the modeling. Just because a model can be built, and run to completion, are not indicators of the appropriateness, yet alone the accuracy, of the results.

No Round Robin starts out too simple, only too complex. Unfortunately, the degree of complexity is never fully realized until the experimental results are compared to the simulations results, after all the resources have been expended. As with the present example Round Robin, little was gained from the exercise, despite a significant amount of resources being expended by a large community. The only positive result from the present Round Robin were the extensive measurements from the purpose built concrete slab repeat tests. However, even this positive result will be greatly diminished if the organizers do not make the data available for others seeking to assess their ability to simulating such experiments.

A few observations and recommendations for future Round Robin organizers:

- Because of the tight time schedule, the benefits of information exchange among calculators, and experimentalist, was omitted – likely the greatest overall loss.
- The program was too rushed – a more ideal situation would have been three self-contained phases, one for each problem definition: Meppen, Bending and Punching.
- The goals of the calculations, i.e. what is important, were not specified. This meant the models needed to equally emphasize all of the various requested outputs.
- Too many problem definition items were either insufficient, e.g. concrete strength envelopes, or lacking, e.g. strain rate properties of missiles.
- Requested calculator reporting information was not vetted – there is a need to have an experienced calculator on the planning & evaluation teams to provide support.
- There is a need for general guidance on conducting validation or round robin exercises.