20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division 4, Paper 1946

Validation of Riera Loading in LS-DYNA Models of Missile Impact*

John A. Vera, Ph.D.[a]

[a]*U.S. Nuclear Regulatory Commission, 11555 Rockville Pike,*
Rockville, MD 20852, U.S.A., John.Vera@nrc.gov

Keywords: Concrete, Impact, Finite Element, Riera Load.

1 ABSTRACT

The VTT and IRSN have used computer codes to predict the effects of impact on concrete structures (Saarenheimo et al. (2007), Tarallo et al. (2007)). These efforts make use of Riera loading to simulate actual missile impact. In the VTT tests modeled, two types of missiles were used: "dry", or hollow cylinder, and "wet", cylinder filled with water. While modeling results have shown good agreement with test data, there are conflicting conclusions regarding Riera loading for "wet" missile conditions. Contrary to results presented by VTT, IRSN authors concluded that Riera loading was inadequate for a “wet” missile case.

The purpose of this paper is to benchmark the finite element code LS-DYNA and determine the adequacy of Riera loading for impact cases reported by VTT. Riera loading is developed and used, as well as the loads from both references, in LS-DYNA dynamic finite element models. Two different material models are used for the concrete. Analyses are also performed with actual impactors.

Results show the displacements and rebar strains obtained from finite element analyses agree very well with experimental results when using Riera loading. Refinement of the load to consider the physics considerably improves results.

2 INTRODUCTION

Interest in impact on concrete structures has led the Technical Research Centre of Finland (VTT) to design a new facility where impact tests could be carried out (Lastunen et al. (2007)). The main purpose of these tests is to calibrate and benchmark numerical models. Among these efforts, Saarenheimo et al. (2007) have used ABAQUS/Explicit to model impact tests 642 and 644 performed at the VTT. Test 642 consisted of a hollow aluminum cylinder missile (dry) aimed at a concrete wall, while test 644 was performed with a missile full of water (wet). Tarallo et al. (2007) have used a computer program described in Rambach (2007) to model these tests. Riera loading (Riera (1968)) is utilized in the computer simulations for both references. Tarallo et al., according to their results, have raised the question of the adequacy of Riera loading for the "wet" case. In their study, they found that the Riera loading as derived by them resulted in a considerable underprediction of system response, represented by a much lower displacement history.

This study also undertook to benchmark LS-DYNA using the available data from the VTT tests. The models consisted of 3D geometry of the concrete walls with Riera loading to simulate the effect of the missile impact. Simple Riera loads were derived and used for these analyses. Two material models available for LS-DYNA were evaluated. This study also used the Riera loading as derived from Tarallo et al. and Saarenheimo et al. to compare the results. As additional comparison, analyses with actual impactors were also performed.

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3 FINITE ELEMENT ANALYSES

3.1 VTT Tests

The concrete walls used in the VTT tests were rectangular solids. The dimensions were as follows: height, 2 m; width, 2.3 m; depth, 0.15 m. Two layers of #8 steel rebar in both horizontal and vertical directions traversed the concrete wall at a spacing of 50 mm. The rebar layers were located 19 mm below the concrete surfaces of the front and back of the wall. The walls were supported on two top-to-bottom parallel supports. A schematic of the walls can be found in Saarenheimo (2007), while the gage setup can be found in Lastunen et al. (2007).

3.2 Finite Element Models

In this study, the finite element model of the concrete wall consists of a full model of the wall. The model dimensions are equal to the actual test wall dimensions.

The wall is modeled with eight-node solid elements. The concrete is modeled using the Winfrith concrete material model (MAT_084), and in separate analyses, with the MAT_159 model. The smeared Winfrith concrete/steel is not utilized in any elements. Instead, the rebar is modeled with LINK160 elements with nodes coincident with the solid elements, using the PLASTIC_KINEMATIC (MAT_003) material model. Boundary conditions were applied to the bottom of the concrete slab as parallel supports that restrain displacements in the Z-direction. They are located 1,100 mm from the center of the slab, in the X direction.

Two loading types were used in the models: Riera loading by way of equivalent pressure, and modeling actual impactors. Details for each method follow.

3.2.1 Riera Method

The impact by an aluminum missile is simulated by a variable pressure. In this study Riera loading was developed using a spreadsheet file. The load is calculated by iteration, which ends when the velocity approaches zero. A load history derived with the Riera method is divided by an area of elements chosen to closely resemble the area of impact. Fig. 1 shows the Riera loads derived in this study.

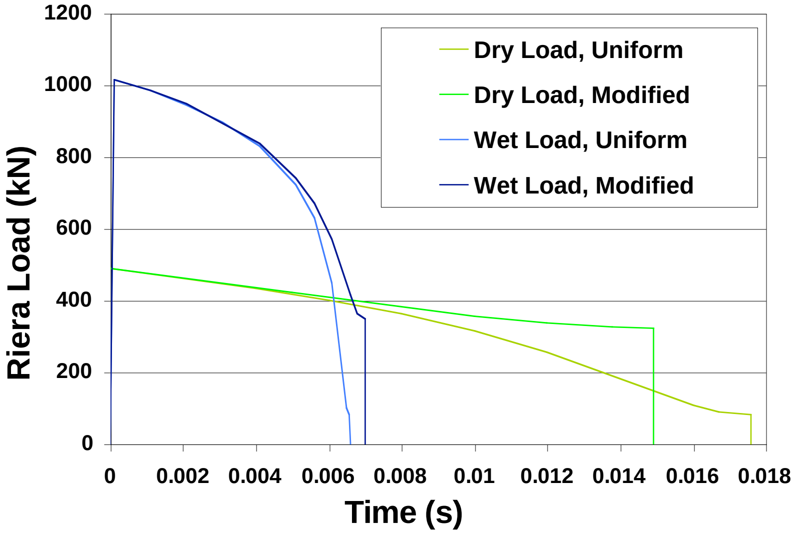


Figure 1. Riera curves as derived in Current Study.

Two curves are shown for each case. For the dry case, in the first instance ("uniform"), the entire mass of the missile is incorporated into the linear density term. For the dry case, this approach overestimated displacements. Taking into account that the steel portion of the missile is stronger, as well as its location at the back of the missile, a refinement for the load was developed which consisted of assuming the steel produced an impact proportional by mass to the initial mass term of the aluminum, that is:

$$P_{st} = P_{al} \times M_{st} / M_{al} \quad (1)$$

where P_{st} is the loading produced by the steel component of the missile, P_{al} is the initial loading produced by the aluminum mass, M_{st} the steel mass and M_{al} the aluminum mass. This approach produced results closer to those obtained in the physical test.

For the Riera load in the "wet" case, assuming a uniformly distributed mass gave slightly lower displacements than those achieved in the test. For the refinement, the same procedure as for the dry load was used when considering the steel portion of the missile. The water mass was considered in the linear density term.

Analyses were also performed using the Riera curves as derived by Saarenheimo et al. and Tarallo et al. for comparison. Results are presented in Section 4.2.

3.2.2 Impactor Models

In these analyses the impactors were modeled explicitly. The missiles were given an initial velocity, taken from Lastunen et al. (2007), equal to 109 m/s for the dry case and 105 m/s for the wet. Several assumptions had to be made due to lack of data regarding missile component weights and material properties. The geometry of the impactors was also simplified, but the total mass was kept equal to the reported missile mass by adjusting the component densities. The missiles were simplified to two and three components for the dry and wet cases, respectively: aluminum and steel for the dry, and aluminum, steel and water for the wet. Certain missile features, such as rails and side plates, were not explicitly modeled. Table 2 lists the missile part volumes, masses and densities as used in the models.

For the concrete wall, the mesh consists of 58,880 hexahedral elements. The global element size in the vertical and horizontal directions is 25 mm. In the depth direction, the element sizes are variable in order to connect the rebar nodes to those of the concrete mesh. The element depths per layer for the 8 element layers, starting at the top surface of the wall, are: 19 mm, 15.5 mm, 15.5 mm, 25 mm, 25 mm, 15.5 mm, 15.5 mm, and 19 mm. The 19 mm depth of the top and bottom layers reflect the depths of the rebar.

The rebar is modeled with 14,376 25 mm link elements, connected to the concrete element nodes. The rebar layers are located 19 mm below the wall surfaces, and have a spacing of 50 mm. Both layers consist of vertical and horizontal rebar, representing the test specimen.

There were two models which included the impactors. For the dry case, the missile consists of two hollow tubes: a 1,500 mm long aluminum tube with a radius of 125 mm, inside a 500 mm long steel tube of radius 136.5 mm. Both tubes were modeled as being closed only at the tail end. 13,360 SHELL163 elements were used for the aluminum, while 6,912 were used for the steel. Fig. 6 and 7 show the wall and missile model, and details of the missile mesh against the backdrop of the concrete wall mesh.

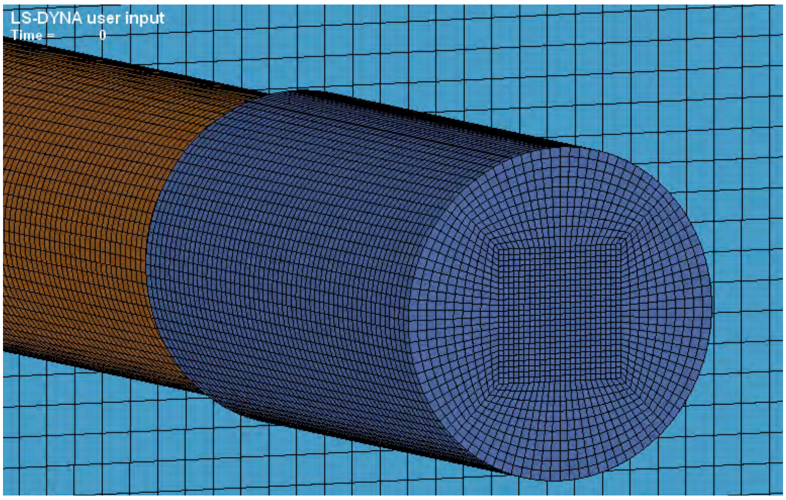


Figure 2. Dry missile impactor mesh.

For the wet case, the missile consists of two hollow tubes and a solid cylinder representing the water. The aluminum tube with radius 25 mm is 600 mm long, and has a 50 mm long steel tube with radius equal to 136.5 mm on the tail end. Both tubes were modeled as being closed only at the tail end. 5,840 SHELL163 elements were used for the aluminum, 1,716 were used for the steel, while 52,880 SOLID164 elements were used for the water. Fig. 3 shows the wet missile mesh (soon after contact in the analysis, thus the deformation), where the steel elements are blue, the aluminum red, and the water yellow.

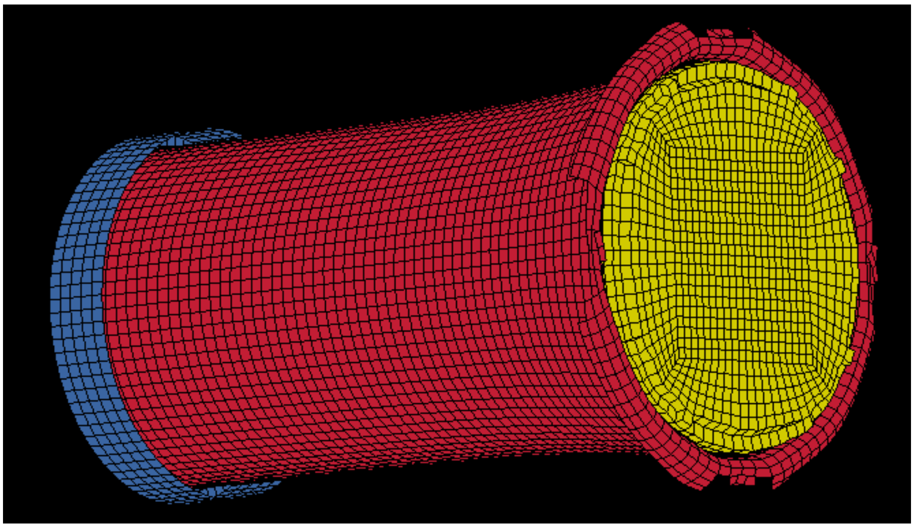


Figure 3. Wet missile impactor mesh.

The concrete was modeled using two LS-DYNA concrete material models: MAT_084 (Winfrith) and MAT_159. A Plastic-kinematic model, MAT_003, was used for rebar and for the aluminum and steel of the missiles. A linear elastic model with fluid option, MAT_001_FLUID was used for the water. For this model, erosion criteria were added in order to simulate the effect of dissipating water. The best results were obtained with erosion at a compressive strain of 0.9. A shear erosion strain of 0.6 was also used in order to erode any elements with extreme deformations due to the erosion of neighboring elements. Such elements can cause problems which can lead to premature termination of the analysis.

Table 1 lists the card values for the parameters of each material model as entered for each analysis. The aluminum and steel models for the dry and wet missiles differ only in the material densities used for each. The values shown correspond to the “standard” models. Other values were entered when evaluating different parameters. The parameter definitions in each material model can be found in the LS-DYNA keyword manual. The rebar and concrete material properties were taken from Saarenheimo (2007). The deformable aluminum properties, along with the Cowper-Symonds values for the model, were taken from Stouffer (1996).

Table 1. Card values for material models.

Material model cards used in LS-DYNA	
Rebar Steel - MAT_003	**Dry Missile Aluminum - MAT_003**
*MAT_PLASTIC_KINEMATIC 10,7.86E-9,0.21E6,0.330,560.0,0.5E3,0.5 40.0,5.0,0.6,1.0	*MAT_PLASTIC_KINEMATIC 30,3.435E-9,0.070E6,0.10,160.0,0.070E3,0.5 6500,4.0,1.0,1.0
Concrete - Winfrith - MAT_084	**Dry Missile Steel - MAT_003**

*MAT_WINFRITH_CONCRETE 20,2.4E-9,3.5E4,0.20,58,2.9,0.092,9.525 2.1E5,5.6E2,0.5E3,0.60,0.0,-4	*MAT_PLASTIC_KINEMATIC 40,7.86E-9,0.21E6,0.330,413.6,0.5E3,0.5 40.0,5.0,0.6,1.0
Concrete - MAT_159	**Water in Wet Missile - MAT_001**
*MAT_CSCM_CONCRETE 20,2.4E-9,3,11,1,0.0,10.5,0 0 58,19.05,2	*MAT_001_FLUID 55,1.0E-9,2.2E6,0.495,,,2.2E6 0.2,2E10 *MAT_ADD_EROSION 55,,, ,,,0.9,0.6,,,

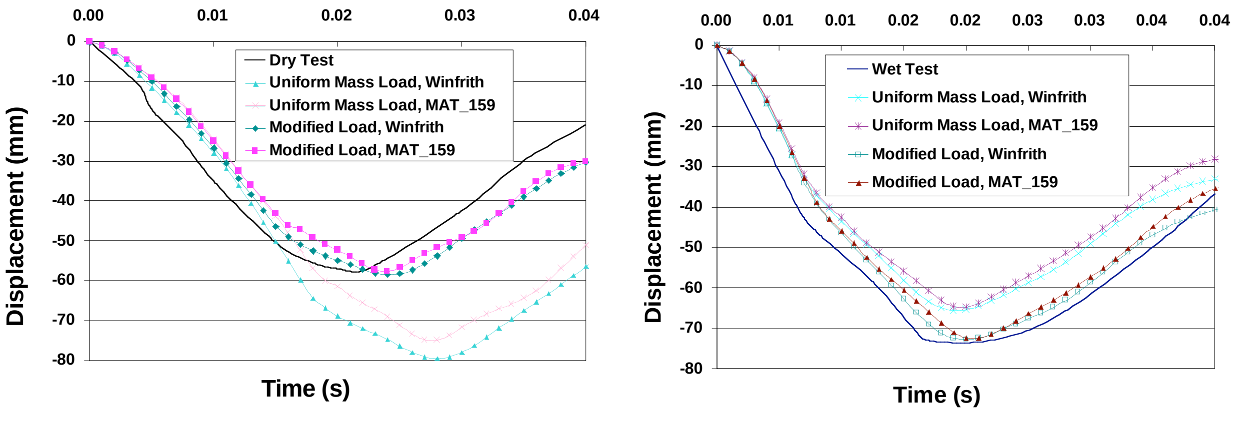
4 RESULTS

The Finite Element program LS-DYNA was used to perform impact analyses simulating actual tests performed in the (VTT). The tests consisted of launching aluminum missiles on doubly-reinforced concrete walls, as detailed on references Lastunen et al. (2007) and Saarenheimo et al. (2007). Models were compared using the wall displacements at strain gage locations.

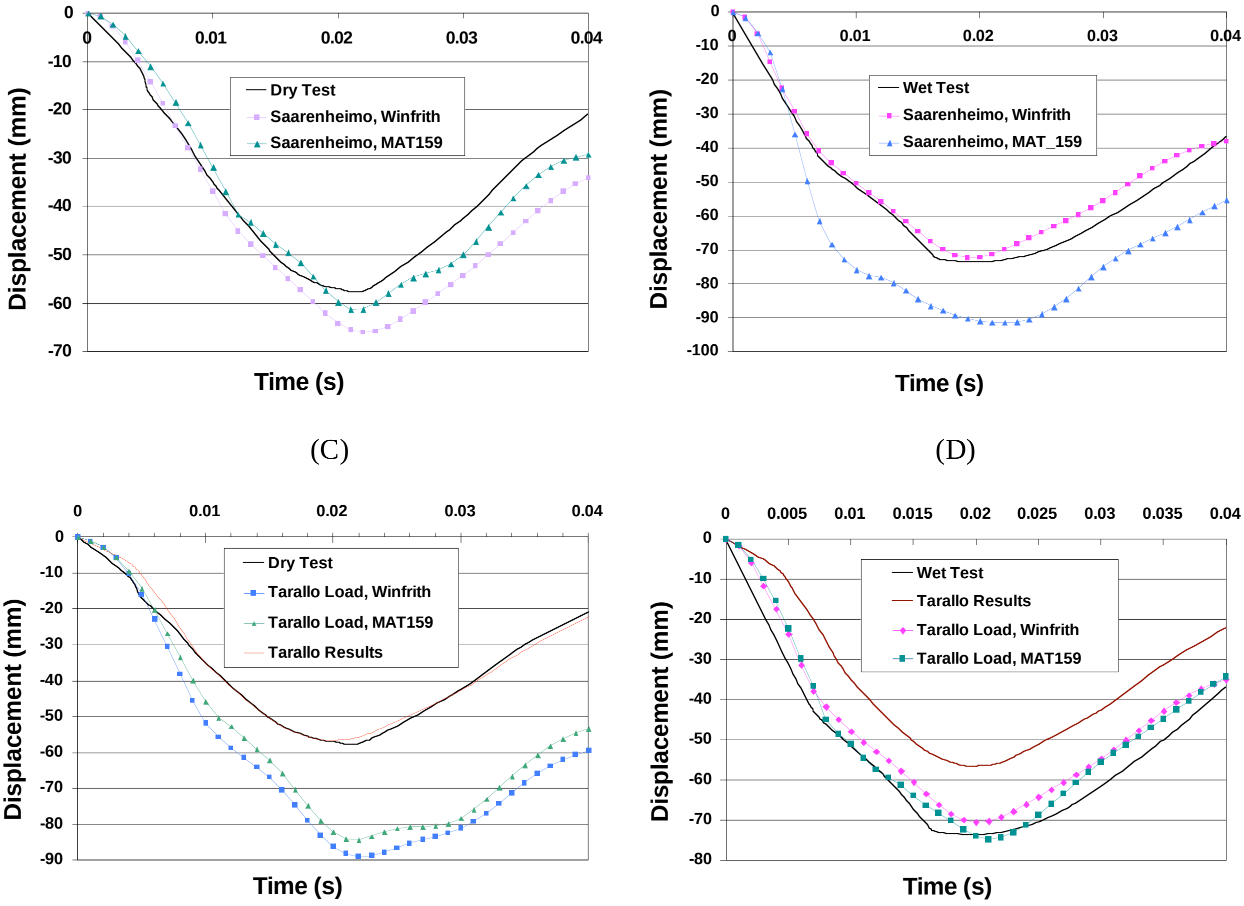
A simple comparison criterion, the displacements at or near the locations of actual test displacement gages, was used. The locations which showed most movement in the tests were used in order to use the most sensitive location. The test displacement gage locations can be found in Lastunen et al. (2007). For Test 642 (dry) the node used was 86556, which coincided with the displacement gage location (gage D1-DRY in Lastunen et al. (2007)). For Test 644, node 87371 was used, which is just 10 mm away vertically from the actual gage location (300 mm below the wall center, versus 310 mm for the gage, D1-WET in Lastunen et al. (2007)).

4.1 Riera Load Results

The results obtained with Riera loading obtained from Saarenheimo et al. (2007) and Tarallo et al. (2007) closely matched the test displacements at the selected displacement gage locations. For the Saarenheimo loads, MAT_159 significantly overestimated the results in the wet case, versus close results using the Winfrith material for both cases. For the Tarallo loads, the results were closer with both concrete models, but the dry case gave significant overestimation of displacements. This is attributed to the load curve. as our calculated total impulse is significantly higher than the one provided by the authors. It is noted that the derivation of the loads is not explained in any reference. The plots in Fig. 4 show the results in terms of displacements at gage locations.



(A) (B)

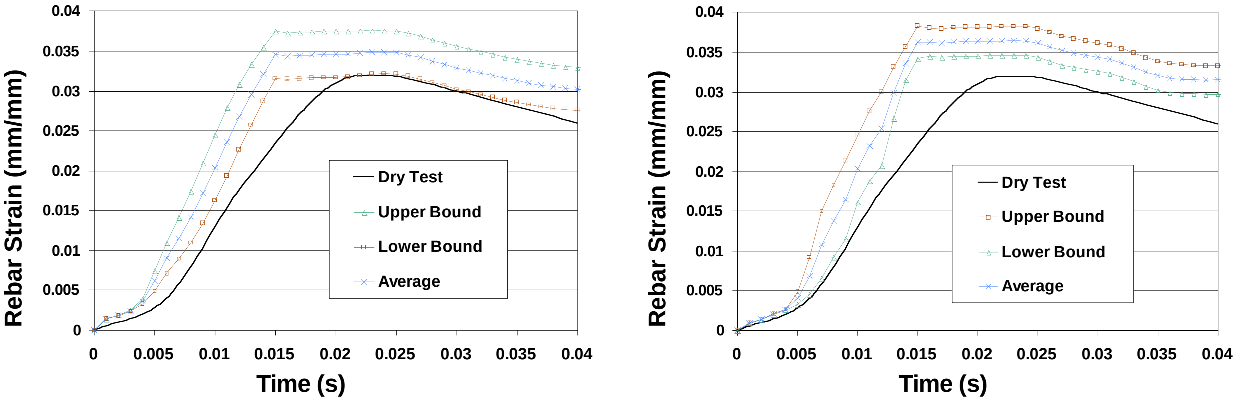


(C) (D)

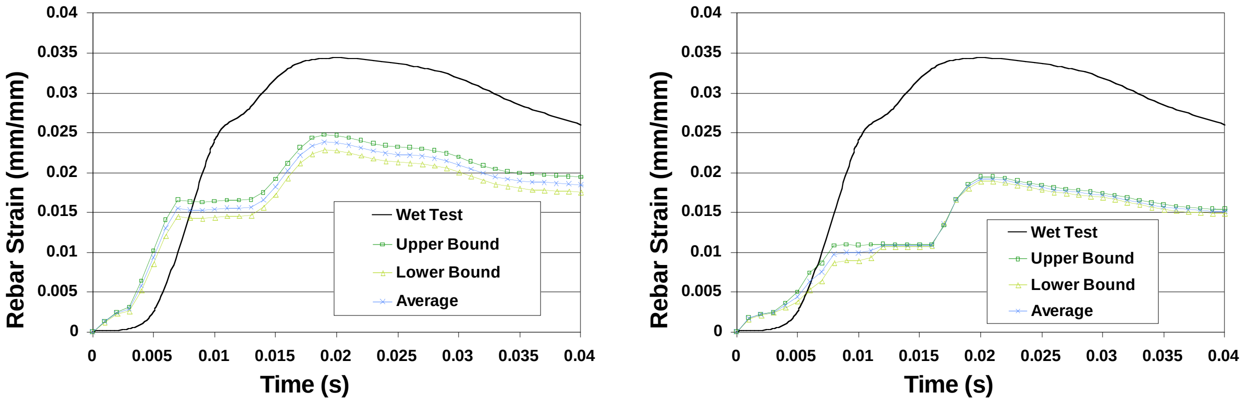
(E) (F)

Figure 4. Displacement versus Time plots A) Dry case, Current Study loads; B) Wet case, Current Study loads; C) Dry case, Saarenheimo loads; D) Wet case, Saarenheimo loads; E) Dry case, Tarallo loads; F) Wet case, Tarallo loads.

Back rebar strains are plotted in Fig. 5. Since the distance between nodes in the model was 25 mm, and the test gages measured over 5mm; to get a general sense of the strain variation, strains calculated from the two node pairs most adjacent to the test gage locations (gage BH3 for the dry test, gage BH4 for the wet in Lastunen et al. (2007)) are plotted, as well as an average of these. As can be seen, in general good agreement was achieved, especially for the dry case. For the wet case, the analyses give lower strains than test values. However, this is consistent with the results obtained by Saarenheimo et al. (2007) using ABAQUS/Explicit.



(A) (B)



(C)

(D)

Figure 5. Rebar Strain versus Time plots A) Dry case, Winfrith; B) Dry case, MAT_159; C) Wet case, Winfrith; D) Wet case, MAT_159.

4.2 Impactor Results

The models with actual impactors also approached the test results, although in the dry case the models in general overestimated the obtained displacements. This was seen to be especially dependent on the assumed mass ratio between the steel and aluminum parts of the missile (steel mass over aluminum mass). In order to correctly gage the accuracy of the finite element model, the missile component weights would have to be known. Another factor that influenced the results was the assumed aluminum yield stress: 160 Mpa was assumed for most analyses. Fig. 6 (A) shows the displacement plots for analyses with varying mass ratios, using Winfrith concrete.

For the wet missile case, the critical factor was the erosion criteria for the water elements. Eroding the elements too soon reduces the momentum transfer, resulting in response underprediction. The erosion criterion was strain based on the compression direction, with an additional criterion for shear strain and orphan element control. It was found that the response converged for erosion at strains of 75% or above. Match with test results in terms of maximum displacement was very good; although it is clear from the initial slope that the momentum transfer occurs faster in the finite element analyses than in the test. Fig. 6 (B) shows the displacement plots for analyses for the wet case. The second drop in the slope in these cases is due to the "push" of the upper and lower sections as they catch up with the center section of the wall.

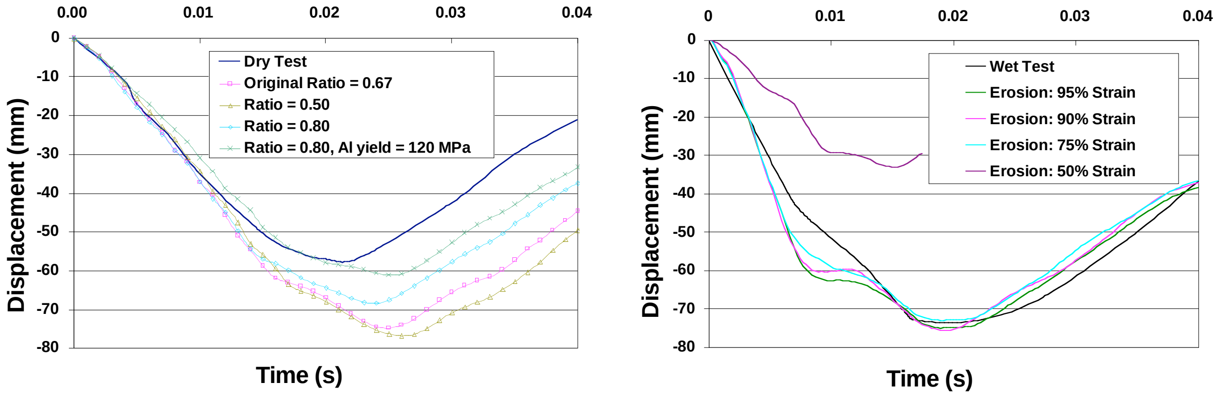


Figure 6. Displacement versus Time plots for impactor analyses: A) Dry case; B) Wet case.

5 CONCLUSIONS

It has been demonstrated that Riera loading can produce good results when applied in a finite element analysis. However, somewhat differing results when considering different sources for Riera loads show the sensitivity of the problem to the derivation of the loads. In our study it was found that in order to achieve the most accurate results, adjustments should be made in the loads for the effects of nondeformable parts of the impactors.

Although the Winfrith model considers cracking and MAT_159 has an option for element erosion; modes of failure such as penetration, perforation and punching have not yet been benchmarked. The suitability of material models must be established for these cases. It is important to remember that Riera loading is based on the assumption that the impacted surface is rigid. If future work involves expected destruction of a loaded portion of the concrete; it is probable that Riera loads will not be adequate to simulate the problem.

Acknowledgements. *The author would like to thank Abdul Sheikh, Dr. Syed Ali, Jason Piotter, Bhasker Tripathi and Dr. Gordon Bjorkman for their input and assistance in the preparation of this work.*

REFERENCES

Lastunen, A., Hakola, I., Järvinen, E., Hyvärinen, J. and Calonius, K., “Impact Test Facility”. Transactions SMIRT 2007.

Rambach, J-M. "Behavior of a reinforced concrete beam under impact loading: a simplified approach". Transactions SMIRT 2007.

Riera, J.D., “On Stress Analysis of Structures Subjected to Aircraft Impact Forces,” Nuclear Engineering and Design, Vol. 8, 1968, pp. 416426.

Saarenheimo, A., Tuomala, M., Calonius, K., Lastunen, A. Hyvärinen, J., and Myllymäkki J., “Numerical studies on impact loaded reinforced concrete walls”. Transactions SMIRT 2007.

Stouffer, D.C., Dame, L.T., *Inelastic Deformation of Metals: Models, Mechanical Properties and Metallurgy*. John Wiley and Sons, New York (1996).

Tarallo, F., Ciree, B., and Rambach, J.M., “Interpretation of soft impact medium velocity tests on concrete slabs”. Transactions SMIRT 2007.