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LOCAL TURBINE MISSILE IMPACTS ON CONCRETE TARGETS

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INTRODUCTION

A turbine failure may lead to fragments being ejected at high velocity, becoming projectiles capable of damaging safety related equipment. United States Nuclear Commission (NRC) requirements require a protecting against such events. One option of doing so is it to provide a protective barrier to maintain the safety of plant systems. Concrete walls are often credited as protective barriers and are typically shown to meet penetration, perforation, and scabbing requirements through code based empirical formulas. However, empirical formulas only account for a handful of variables (e.g., steel reinforcing ratio is excluded) and may oversimplify the problem (e.g., the use of generic coefficients to account for deformability). The use of finite element analyses to assess a turbine missile impact may lead to cost savings (i.e., thinner walls, less reinforcement, fewer mitigation strategies) when compared to assessments using empirical formulas as the analyses will better represent the specific impact of interest.

This paper presents a study to examine postulated turbine missile impacts on reinforced concrete walls through comparisons between experimental test data, finite element analysis (FEA), and established empirical formulas. The analyses include both deformable and relatively rigid projectiles, and three missile geometries: a rod, a turbine blade, and a hemispherical portion of a turbine rotor. Several inputs are varied within the study including the missiles initial velocity, orientation, and material properties. The comparison shows that the rod analysis results trend with the empirical equations. However, the empirical equations overpredict the penetration of the slender turbine blade that exhibits significant deformation during impact. In some cases, the empirical equations show unsatisfactory performance while the finite element analyses show the protective barrier is maintained.

CONCRETE MATERIAL MODEL

A key component in evaluating high energy impact scenarios is the constitutive representation of the concrete material. For these studies, this concrete material performance is provided through Structural Integrity Associate's (SI) proprietary ANACAP constitutive concrete model within the Teragrande explicit finite element code (TG). The concrete constitutive model is based on a smeared cracking methodology and has been developed and improved for over 40 years with extensive use in implicit and explicit finite element codes.

A thorough description of ANACAP's features is not presented herein, but a brief discussion is warranted. The behavior of concrete is highly nonlinear having a small tensile strength, shear stiffness and strength that depend on crack widths, and compressive plasticity. The key components of the concrete performance for this class of problem include tensile cracking, post-cracking shear performance, and compressive yielding when the compressive strength is reached while also accounting for the effects of confinement and strain rate effects. For explicit, high energy impact analysis the strain rate effects of concrete are significant and are represented within the concrete constitutive model as wells as the aforementioned behaviors.

VERIFCATION AND VALIDATION

A set of verification and validation problems were performed to provide a basis that the analysis methodology using TG-ANACAP FEA for evaluating high velocity, small deformable projectiles impacting reinforced concrete targets is viable. Testing results were pulled from three reports to qualify different concrete strengths, impact velocities, and projectile shapes. Published in the "International Journal of Impact Engineering" from Frew, Hanchak, Green, and Forrestal, and from a technical report published by the U.S. Naval Weapons Laboratory by Canfield and Clator.

From these published data sets several validation problems were selected such that the mass, projectile shape, and velocities were within a bounding range of the expected turbine postulated accident conditions. Tests were simulated with finite element analyses and calibrated with a reasonable mesh density. Results show good correlation with the test data with a similar coefficient of variation expected of concrete strength, Figure 1. The mass here is the primary difference between the physical test data and that of the postulated turbine missile fragment. The reason for selecting the small penetration objects is that it correlates to the leading edge of a turbine blade. In this study the postulated missile is oriented to produce maximum damage. Therefore, the leading edge of the blade, which is thin and would be expected to have the furthest penetration, correlates well to the small impactors of the physical tests.

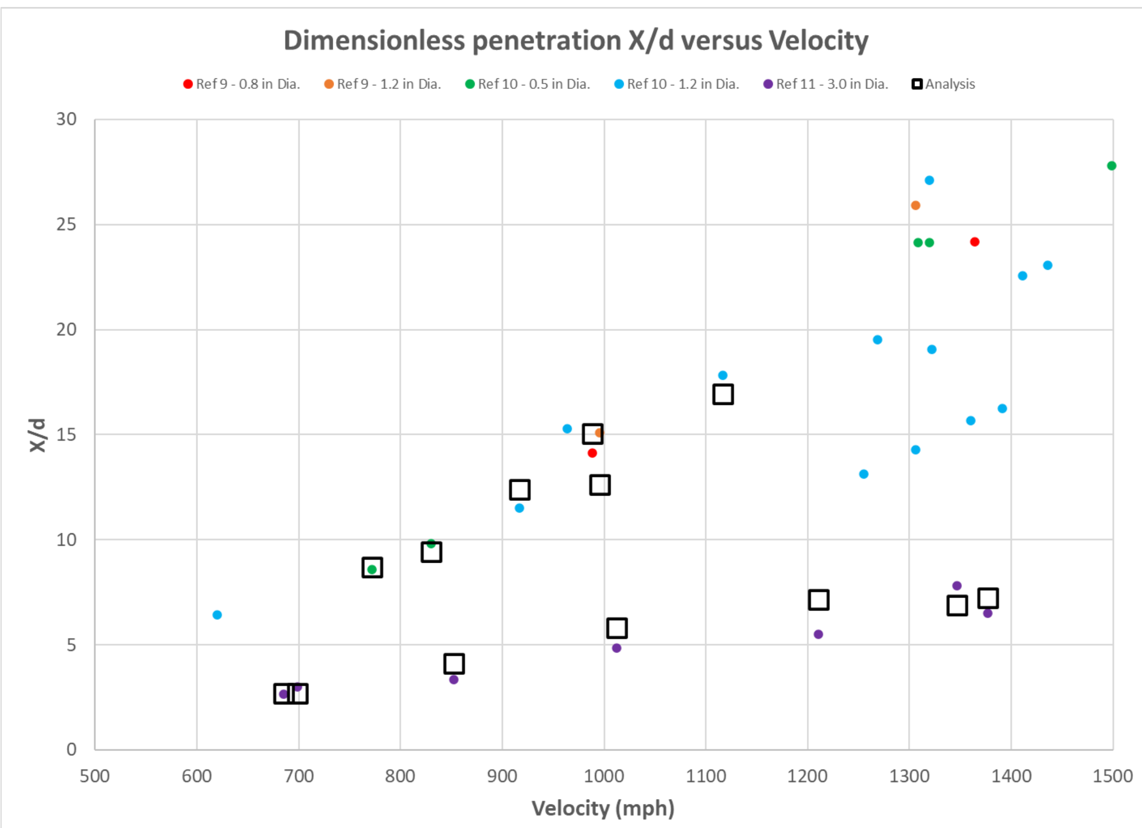

Figure 1. Penetration Depth/Diameter (X/d), Test Data Compared to Analytical Simulation

A second set of verification and validation problems were conducted for the larger rotor impact. This further showed the viability of the concrete material model and correlate with the larger impact penetration depth calculation. The physical test data was obtained from an Electric Power Research Institute (EPRI) test conducted on full scale turbine rotor fragments. Results show an acceptable performance of the concrete material model to perform under this weight and size of an object striking a reinforcement concrete structure, with a penetration depth of 28” predicted to 25.6” actual.

THE ROD MISSILE

Historically a rod missile has been used to represent a turbine blade fragment, essentially because empirical formulas are not available for complex objects such as a turbine blade or rotor. When assessing the NRC requirements, a simplified empirically based calculation assumes that the turbine blade can be represented as a perfectly rigid rod that is 1.41-inches in diameter with equivalent mass and velocity of the blade fragment. The 1.41-inch diameter rod has the equivalent area of the leading edge of the turbine blade. Simple calculation using the empirical formulas would indicate that the turbine blade represented in this way would completely perforate a concrete wall of 60-inches thick at the initial velocities considered for this study. The rod was reproduced in the FEA to corroborate the empirical formula and included impact evaluations with varying initial velocity of the rod missile. In addition to a 1.41-inch diameter rod a 2.00-inch rod was selected to provide a bounding upper case. Figure *2* show the penetration depth of the 1.41-inch and 2.00-inch diameter rode at variable initial velocities as well as curves for various empirical calculations. This confirmed that a 1.41-inch diameter rod would penetrate the 60-inch-thick concrete wall. The figures are plotted with results using the empirical equations developed at the Natural Resources Defense Council (NDRC), Amman and Whitney (A&W), and the Army. These results indicate that the FEA methodology aligns closest with the empirical equation developed by the Army.

These empirical equations assume that the rod is “rigid” (no energy dissipation). In reality the missile will deform and dissipate energy. For the analytic evaluation, the material properties allow the rod to deform, although included strain rate effects increase the rod stiffness under velocity, additionally the rod has imposed geometric stiffness due to modeling as quarter symmetry (the rod is unable to buckle out-of-plane). Therefore, the rod has characteristics of acting rigidly but still dissipate energy in the simulation much as it would in the physical test specimens. Figure *2* for the 2.00-inch diameter rod (right) marks the penetration depth of the 2.00-inch diameter rod analysis with a computational rigid material model. This highlights the difference between the computational rigid material in analysis and what a physical test would consider “rigid” material while still allowing for energy dissipation through the impactor. The target block in the analysis is a free standing 4-foot by 4-foot square, no reinforcement.

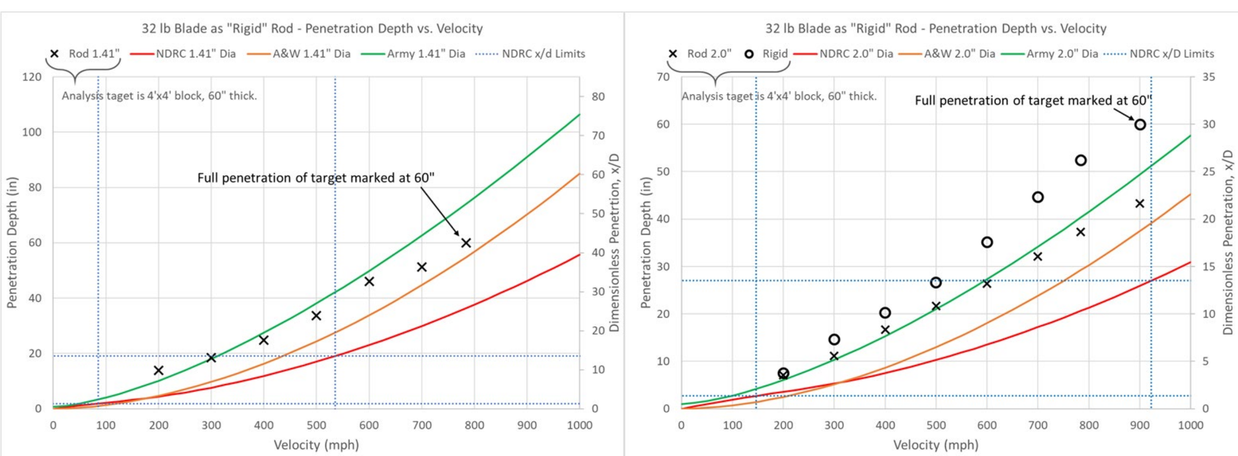

Figure 2. Variable Velocity Penetrations, 1.41-inch Rod (Left) and 2.00-inch Rod (Right)

THE BLADE MISSILE

Using realistic geometry for a blade fragment impactor instead of the rigid rod reduces the penetration depth calculated. This is attributed to factors including geometric shape, nonlinear material properties, and allowing a deformable missile. As a baseline comparison it is assumed the turbine is operating at 120% overspeed at the time of failure. The overspeed translates directly to the initial velocity of the missile. Figure 3 shows the concrete strain in the target for the analyses with the simplified rod representation of the turbine missile, the 1.41-inch rod fully penetrates the 60 inches of concrete with a residual velocity. The 2.00-inch rod is stopped after penetrating 42.3".

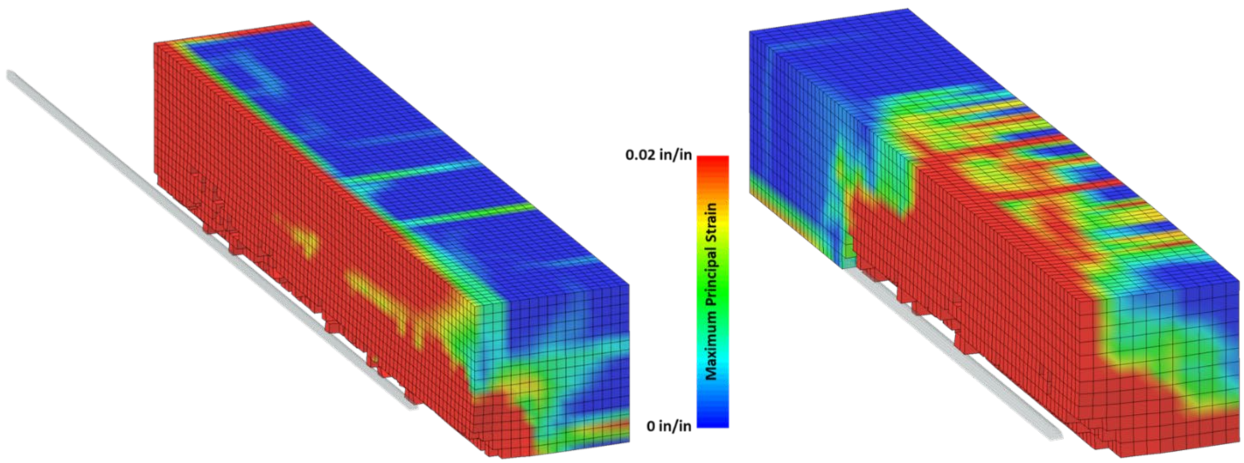

Figure 3. Concrete Strain and Rod Penetration for 1.41" (Left) and 2.0" (Right) Diameter Missiles

This is compared to an analysis utilizing realistic geometry of the blade, with the material properties of the blade defined to act as a rigid body. A penetration depth of 54.6 inches is observed as the blade stops within the concrete block. The reduction due to geometry places the penetration between the 1.41-inch rod and the 2.00-inch rod. During this analysis case the concrete block was assumed to be a 4-foot square section of a larger wall albeit with unconfined boundary conditions around the perimeter of the block. Realistically, the surrounding wall would provide confinement to the small domain of the analytic target block. A second analysis was performed with symmetry boundary conditions applied around the perimeter of the block to simulate the confinement provided by the full wall section. This simulation calculated a penetration depth of the blade to be 44.2", a 19% decrease. Figure 5 show the concrete strains in the concrete block and the time the blade has stopped, zero velocity for the unconfined and confined conditions.

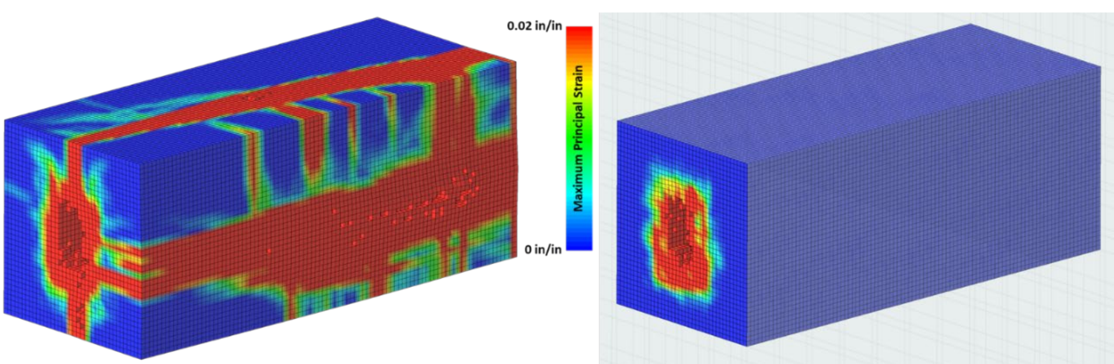

Figure 4. Rigid Blade Impact, Unconfined (Left) and Confined (Right).

Analyses were performed to evaluate the penetration depth when including realistic material properties for the turbine fragment in addition to representing the blade geometry, referred to as the blade impactor. This resulted in a calculated penetration depth of 20”. Figure 5 shows contours of velocity and deformation of the bade fragment from initial impact of the blade until it comes to a stop. These show the deformation and buckling of the thin section at the tip of the bade. This is the primary factor in reducing the penetration depth as the deformation of the blade tip enlarges the leading-edge profile which increases the contact area and dissipates additional energy.

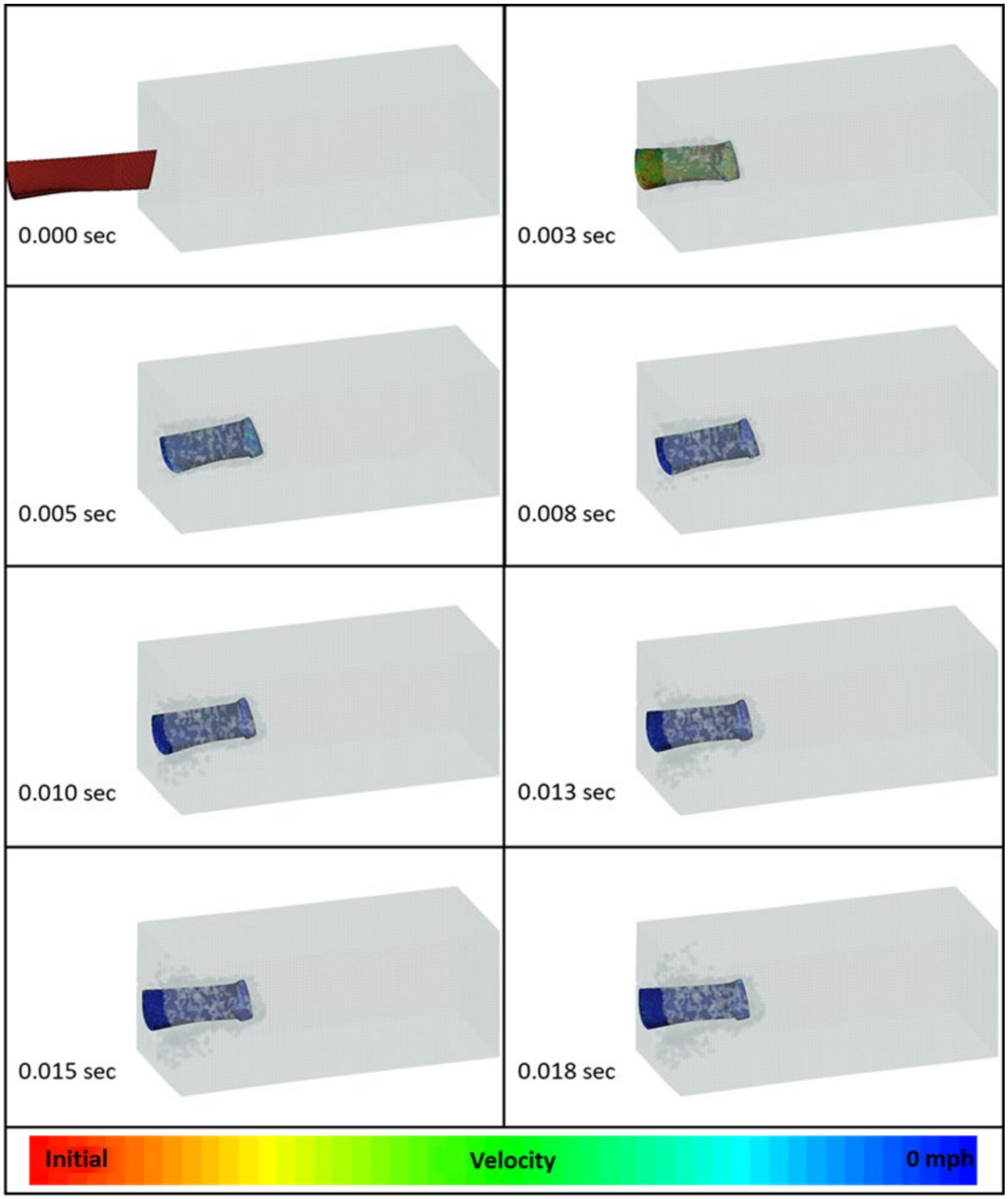

Figure 5. Velocity and Blade Deformation During Impact Simulation

To evaluate the disparate differences in the calculated results between using a rigid rod impactor versus the blade impactor, analyses were performed with the impactors striking a rigid wall. This allows the calculation of the contact force and impulse of the impactors while removing the response of a compliant target. Figure 6 shows the contact force and impulse of the of the different representative turbine missiles hitting striking a non-compliant target. The results indicate that the initial impact of the rods are front loaded compared to the more distributed loading imparted by the blade model. The impulse shows the two rods bookend the blade in terms of total impulse. The initial slope of the impulse of the rods is larger due to their rigidity while the blade missile begins to deform upon initial impact delaying the transmission of the full impulse into the target.

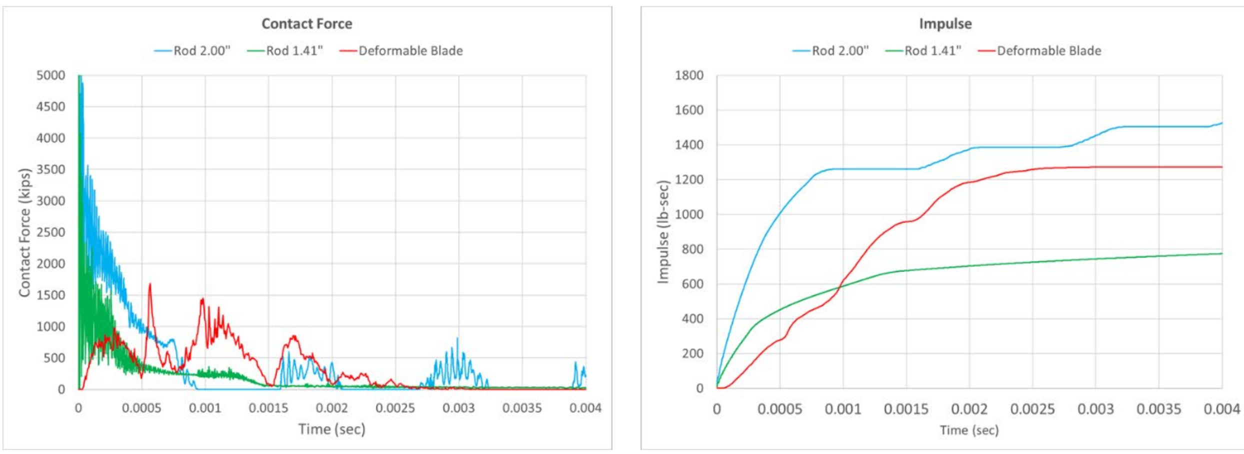

Figure 6. Contact Force (Left) and Impulse (Right) of Impactors Striking a Rigid Wall.

Utilizing the blade impactor, two additional analyses were performed assuming failure of a blade at 160% and 180% overspeed. The calculated penetration depth for these cases was 25 inches and 29 inches respectively, shown in Figure 7.

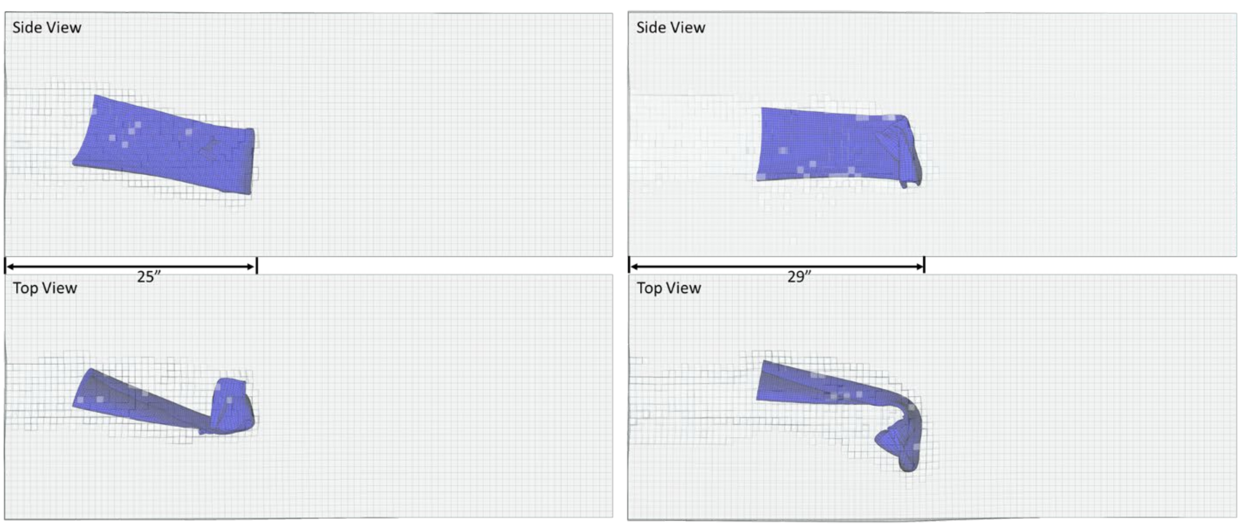

Figure 7. Penetration Depths at 160% Overspeed (Left) and 180% Overspeed (Right)

Further refinement during this study entailed modifying the blade impactor to include a segment of the blade root, increasing the mass of the missile. To accommodate the larger impactor the size target wall was enlarged. The mesh for the blade with root and a section of the wall at the impact location is shown in Figure 8. Reinforcement bars were included within this wall segment although the new impactor is still small enough to pass through the wall without striking the reinforcement due to the assumed spacing.

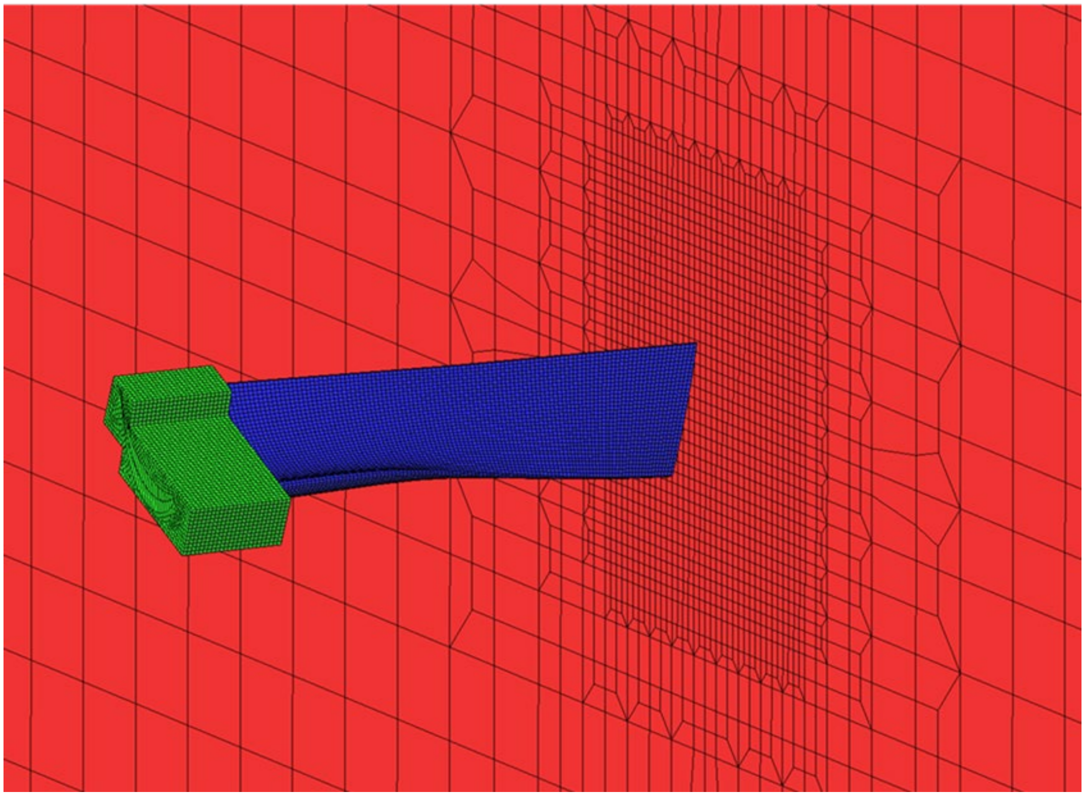

Figure 8. Blade With Root and Concrete Wall Mesh.

The simulation was conducted with varying initial impact velocities up to 220% overspeed. Results from the simulations are summarized in Table 1. The penetration depth is shown for the 180% and 190% overspeed cases in Figure 9. There appears to be a disparity between these two cases, 180% and 190% overspeed, showing a decrease in the penetration depth of the missile when the penetration depth would be expected to be increasing. This is due to the indeterminate buckling of the blade during the nonlinear calculation that can be seen in Figure 9. To show that conservation of energy is still being observed (increase in velocity leads to an increase in penetration depth) the penetration of the root was tracked. The measurements of the root penetration indicate that with increased velocity the penetration depth of the root also increases.

Table 1. Summary of Penetrations Depths for Blade-Root Impactor

Case	Overspeed	Penetration Depth (in)	Root Penetration Depth (in)
1	120%	17.0	2.1
2	140%	21.5	6.7
3	160%	24.0	8.9
4	180%	26.0	10.8
5	190%	25.5	11.2
6	200%	26.0	11.9
7	210%	28.5	14.0
8	220%	28.5	14.3

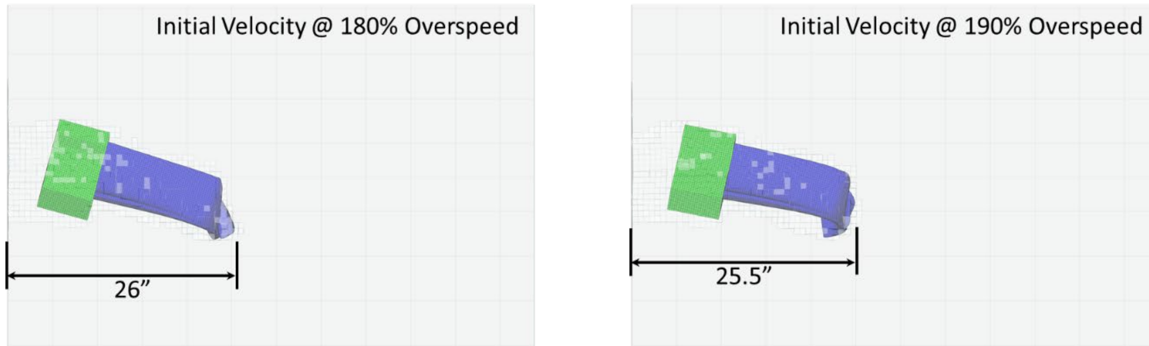

Figure 9. Deformed Blade at Zero Displacement, 180% (Left) and 190% (Right) overspeed cases.

THE ROTOR MISSILE

The rotor missile was developed as a simplified hemispherical section representing the turbine rotor. Analyses were performed with two strike angle alignments at initial impact. One with the rotor edge perpendicular to the wall and second with the center of gravity (CG) aligned through the tip of the rotor and perpendicular to the wall. Figure 10 shows the alignment at the top of the figure and the final penetration position of the rotor for the two alignments and three overspeed cases. Concrete cracking in the wall and plastic strain in the reinforcement for the 160% overspeed case with the alignment through the center of gravity is shown in Figure 11. The wall thickness evaluated for the rotor strike is still 60” thick and can contain the penetration of the rotor.

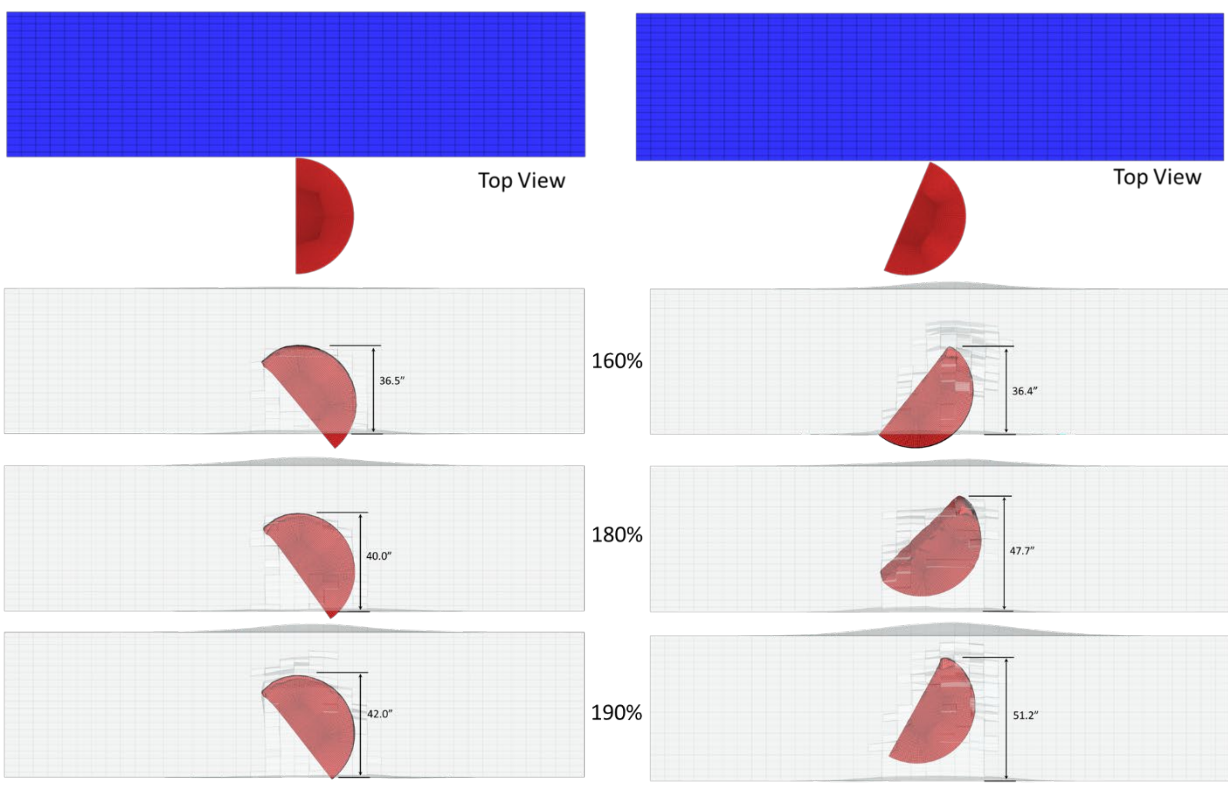

Figure 10. Penetration Depth of Rotor, Perpendicular Alignment (Left) and CG Alignment (Right)

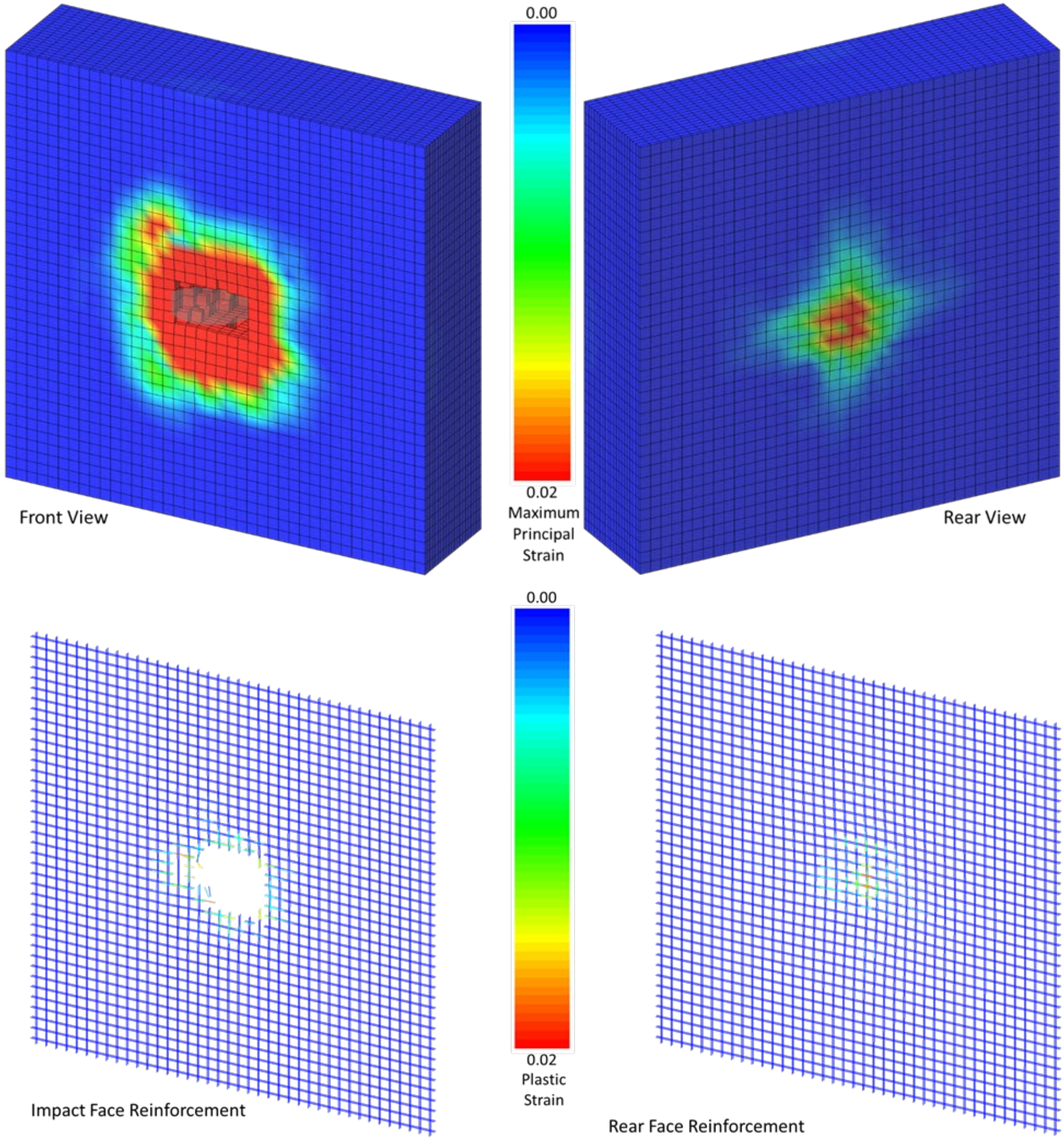

Figure 11. Concrete and Reinforcement Steel Damage With Rotor CG Alignment at 160% Overspeed.

CONCLUSION

The finite element analyses of postulated turbine missile impacts show that a 60” thick concrete wall is able to contain the different projectiles. This is contrary to empirical analysis showing an unsatisfactory result assuming the turbine missile is a rigid rod. These analyses show that the analytic methodology using the TG- ANACAP code performs well in addressing the penetration depth of complex objects.

A secondary aspect of this type of analysis is perforation and scabbing requirements of the wall. The perforation and scabbing were not fully explored in this study, but evaluations are required for NRC approval. Currently the TG-ANACAP code has not been validated for perforation and scabbing assessments due primarily to the availability of experimental test data that can be utilized for a validation ad verification exercise. The perforation and scabbing required thickness can be calculated using the NDRC formulas based on the analytically calculated the penetration depth. Further research and development of the analytic tools is ongoing such that they can be used predict the scabbing that may occur in concrete walls due to high energy small projectile missiles.

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