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ASSESSMENT OF REACTOR COOLANT PIPE WHIP ON REACTOR CONTAINMENT WALL

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ABSTRACT

Nuclear power reactor containments are the final barrier to the release of harmful radiation to the general public that can result from a beyond design basis accident. This important function requires that the structural integrity of the concrete containments must be maintained so that this important function can be fulfilled. Under a postulated beyond design basis accident, a portion of reactor cooling system large diameter piping is assumed to break in a guillotine manner such that a high energy projectile is generated, and it impacts the reactor containment wall. Two scenarios are considered for this high energy missile like impact. A direct frontal impact where the whole length the pipe projectile impacts the containment wall. The second scenario considers a glancing impact where the impacting pipe is expected to just rub and slides away after contacting the containment wall. The purpose of this assessment is to find out if the structural integrity of the reactor containment remains intact or it is jeopardized by this postulated high energy/high velocity impact. Non-linear contact and plasticity explicit analyses will be carried out using LS-DYNA computer code to predict damage to containment concrete structure & failures in containment metallic rebars. This paper intends to discuss survivability of nuclear power reactor concrete containment under a postulated high energy projectile impacting the containment wall. An assumed reactor cooling system pipe break generates a fast-moving projectile. Full frontal impact and glancing side impacts are investigated. Explicit finite element analysis code LS-DYNA is used to carry out combined non-linear contact and material plasticity analyses to investigate concrete and rebar damage. The conducted analyses suggest that under certain conditions, the reactor containment boundary wall may not survive high energy missile impact from a fast-moving reactor coolant pipe projectile.

INTRODUCTION

As a general nuclear power plant design philosophy, it is important to recognize the role of redundant barriers that are built into the design of NPP safety systems. The typical barriers, among others, include the containment building, which controls any release of harmful radioactivity from escaping to the public/environment. A massive robust containment system made from reinforced concrete structure with walls 1.5 m thick or more, is provided for nearly all modern power reactors to mitigate the effects of the postulated heat transport piping break. As a minimum, the structures have been designed and constructed in accordance with the requirements of the national building codes or applicable national standards of the host country [R-1, R-2]. The containment structural integrity is checked for stresses & strains caused by various load combinations to ensure containment structural integrity. Pressure load arising from flashing of the heat transport system coolant is generally a major design parameter for the containment design. However, the missile generating from breakup of steam turbine blade(s) are also considered as a design input. But any specific missile impact or pipe whip on the containment were not specifically analysed, at least during the early years of nuclear power reactor containment design.

ISSUE DEFINITION

The loss of coolant accident (LOCA) and its aftereffects in the form of a pressure load on the containment is always a concern for the nuclear regulators. The nuclear plant owners/operators try to alleviate the LOCA concerns and assure nuclear regulators in various ways such as declaring the LOCA as an extremely low probability event or by use of thresh hold break size argument that a pipe size more than a certain diameter is not likely to break. The use of leak before break (LBB) of PHT system coolant piping or provision of rigid barriers are also used to satisfy the nuclear regulatory bodies.

The only missiles of any sort which are considered for the containment design are the small mass steam turbine blades that can break from its rotor and fly into the containment and breach the containment boundary. On the other hand, for a postulated guillotine break of PHT piping, a plastic hinge can form, and the large diameter high energy pipe can whip/impact the containment wall with a tremendous impact force. The regulatory bodies had this concern that containment boundary may be breached. And that too, to an extent that resulting consequences can be quite severe and the NPP may not meet its safety goals. Because of lack of analytical tools and high-speed computers, it was difficult for the owners/operators of early NPP designs to prove analytically that their containment design would withstand such a pipe whip impact. With present day advances in analytical methods, non-linear explicit analysis software and high-speed computers, it is possible to study the impact of large diameter high energy piping breaks and how they affect the containment design. This type of exercise can go a long way in either assuring the nuclear regulators that containment designs are safe against pipe whips or help modify the containment structural design to meet its safety goals.

PROPOSED ANALYSIS METHODOLOGY

The re-enforced concrete containment's structural integrity under the influence of a large diameter high energy pipe impact is assessed by finite element methods numerical analysis. The concrete containment impact analysis is a very complex structural phenomena involving material non-linear behaviour, contact among various surfaces and concrete and steel rebars coupling at the same time. LS-DYNA Explicit dynamic analysis software [R-3] is used to simulate the time dependent impact analyses.

The analysis methodology involves two distinct types of motion of the whipping pipe which results from an assumed pipe single guillotine break. The heat transport system can be visualized as a spring with a lot of energy stored in it, like 2500 Mega Jules of nuclear fission thermal energy at any given instant that gets released when the large diameter pipe breaks. The broken pipe develops a pipe plastic hinge and moves with tremendous velocity and thus impacts the re-enforced concrete block either hitting the concrete block head on i.e., a direct frontal impact or by a linear biaxial velocity pipe motion in which the pipe hits the concrete block while moving at an angle from previous frontal impact. A punching type of impact analysis was not considered because it would require a free missile which can only be generated by a double guillotine break which is almost impossible to happen. Further with a pipe motion about a plastic hinge, it is not possible by the pipe to impact the concrete block with its circular side face. The results from each type of impact analysis are assessed individually first and then concrete block and the steel rebar's structural performance is compared for the two types of pipe whip impacts and finally conclusions can be drawn from the simulations based on the overall results. The mass loss from material erosion is not tracked.

Analysis Assumptions and Simplifications

Modelling of NPP containment and performing an impact analysis is a daunting task which cannot be performed without the use of some simplifications and few judicious assumptions. Because the NPP containments are of proprietary design, it is next to impossible to get the exact dimensions to build the analysis models and carry out impact analyses. Hence the following assumptions and simplifications were made in building the models and carrying out impact simulations:

I. Concrete containment block model dimensions are obtained from literature search and the block dimensions are 4m length by 4m width and 1.75m thickness.
II. There are two sets of vertical and horizontal rebars (cross meshes) embedded in the concrete block. One set is located near the containment inside surface (within 100 mm) and the other set is placed closer to the outside surface (within 275 mm) of the block outside surface. Figure 1 shows the makeup of the concrete block with rebars and the associated dimensions.
III. The rebars material is modelled with LS-DYNA PLASTIC KINEMATIC (MAT_003) and failure strain is set at 20%.
IV. The impacting pipe's linear velocity is assumed as 500 m/sec. This assumption is based on the coolant discharge rate of 13000 litters/second with an enthalpy of 1412 kJ/Kg. For slanting impact, the pipe is rotated 15 degrees about Y-axis and two velocity components are applied in X and Z such that the resultant velocity is perpendicular to the rotated pipe axis.
V. Compressive strength of concrete is set at 25.0 MPa.
VI. Concrete failure is modelled with LS-DYNA *MAT_159 (*MAT_CSCM(_CONCRETE)) which has built-in parameters for concrete. Elements are deleted when principal strains exceed a certain threshold.
VII. Steel pipe material plasticity is not considered, and it remains elastic during all simulations. It is conservative approach as the energy is used to deform the concrete block.
VIII. The impacting pipe is assumed full of water and the pipe density includes weight of water contained in the pipe.

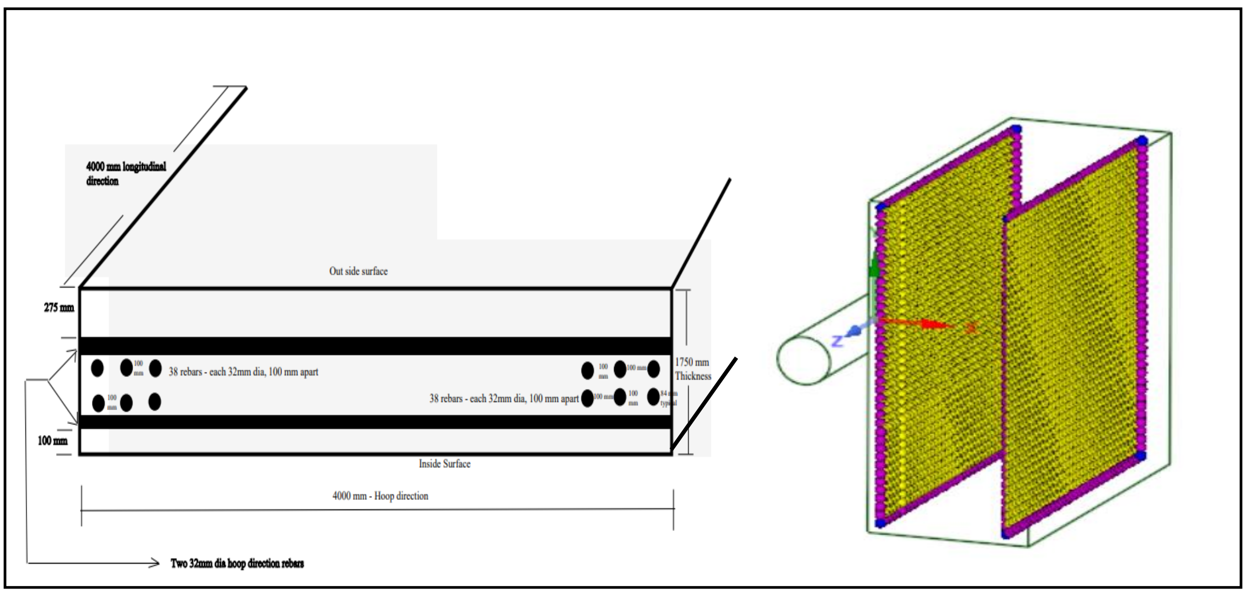

Figure 1. Concrete block and rebar layout with typical dimensions

Analysis Model

The model geometric dimensions as stated in the prior section, were used to create geometry of the complete model in ANSYS SpaceClaim software [R-3] and meshing was done in ANSYS Workbench[R-3]. The data was then brought into LS-PrePost [R-4] to complete the analysis input file. The finite element analysis model contains four parts namely, concrete, pipe, rebar-near and rebar-far. The FE model is shown in figure 2 (The rebars are hidden in the concrete in this figure). The global co-ordinate system is placed at centre of the steel pipe halfway along pipe length. For direct frontal impact, the distance between pipe and concrete block is 500 mm. For slanting impact, the pipe is rotated 15 degrees as shown in figure 2 (right view) below.

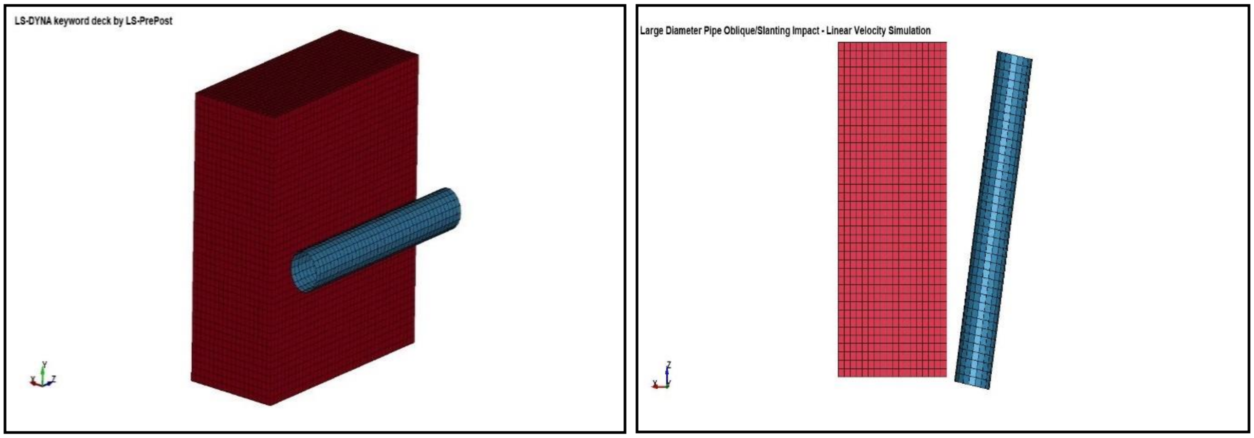

Figure 2. Analysis FE models (Rebars are not visible in hidden line assembly plot)

The target concrete block (4m x 4m x1.75m) is modelled with 28,800 8 node solid elements. The impacting heat transport system pipe is NPS 24" (610mm diameter, 31 mm thick) and is 4m long. The mid thickness surface is modelled with 720 shell elements. Both near and far rebar sets are modelled as beam elements (32 mm diameter solid rod cross section). Each rebar set consists of horizontal and vertical solid steel rods and is meshed with 2964 beam elements each. To control the explicit dynamic analysis time steps, the mesh discretization was nearly uniform. Contact was set up between the steel pipe and the concrete block and between steel pipe and each of the rebars. Contact transducers are used to record contact forces produced by defining the slave and master sides between contacting parts. The generated contact forces data written in RCFORCE file using contact transducers, was extracted for post processing of contact forces between various contacting parts of the analysis model.

The coupling between concrete block solid elements and the rebar beams was achieved though *constrained_solid_lagrange option instead of *constrained_beam_in_solid. To use the selected option, the beams were meshed in such a way that all beam elements of both rebar sets shared common nodes with concrete block solid elements to couple properly. The analysis termination time was set at 0.035 seconds (35 milli seconds).

Materials and Material Properties

For containment concrete block LS-DYNA material 159 (*MAT_CSCM_CONCRETE…) was used with density of 2.3E-9 ton/mm^3. The parameter 'ERODE' was set at 1.10 and parameter 'FC' was set as 25.0 MPa.

For both sets of rebars, LS-DYNA material 003 (*MAT_PLASTIC_KINEMATIC…) was used with density of 7.85E-9 ton/mm^3. Yong's modulus of 2.0E5 MPa and Yield strength of 250 MPa. Tangent modulus was set at 1450 MPa. Material failure strain was set at 0.20, i.e., (20%).

For the heat transport system pipe (the impactor), LS-DYNA material 001 (*MAT_ELASTIC…) was used with density of 1.94E-8 ton/mm^3. Yong's modulus of 2.05E5 MPa and Poisson's ratio of 0.29.

Loads and Boundary Conditions

The following boundary conditions were imposed on the FE model. Symmetry boundary condition was applied on the concrete block nodes on the two sides (i.e., Uz= 0). The top and bottom side nodes of the concrete block were fixed in Y-direction, i.e., Uy=0.

For the direct frontal pipe impact simulation, the whole part (steel pipe) is given an initial linear velocity of 500 m/seconds in the global X direction. For the slanting impact simulation, because of rotated pipe orientation (15 degrees), the 500 m/sec velocity vector was decomposed into X direction velocity of 483 m/sec and the Z direction velocity of 129.4 m/sec.

ANALYSIS RESULTS FROM TOW IMPACT SIMULATIONS

The results of two different types of pipe impact simulations are presented below. First, each impact simulation results and observations from post processing of the results are described qualitatively in some detail. Then the detailed quantitative results are presented in the comparison of results between the two impact type analyses later. The impact analyses showed many concrete and rebar elements failing after reaching their failure criterion and deleted by the solver program from further analysis solution. The progression of damage to concrete and the rebars is a time dependent phenomenon and it could not be shown graphically without animation. So, it is decided to present a comparison of the two simulation results with graphs in the ‘Comparison of Results’ section below with results from deleted and remaining elements to show the time when the elements reach their failure criteria and start to delete.

Linear Velocity – Direct Pipe Missile Impact

The steel pipe makes first contact with concrete containment block at around 2 milli seconds into the simulation. Extensive damage to concrete surface results after pipe penetrates the concrete block. The program output listing file shows many concrete elements failing and being removed from analysis simulation as they reached the failure criterion. Both ‘rebar-near’ and ‘rebar-far’ part beam elements fail completely (i.e., plastic strains reaching the failure criteria) as the steel pipe passes through them. The back side of concrete bock shows significant damage to concrete block as well. The steel pipe continues to travel after passing through concrete block till the simulation termination time (35 milli seconds). The simulation results suggest concrete block failure as the impacting steel pipe missile passes through the concrete block causing extensive damage to concrete block and both the rebars.

Linear Velocity – Slanting Pipe Missile Impact

As the simulation proceeds, the end side of the steel pipe impacts the concrete containment block immediately and concrete block penetration starts. The middle and upper portions of the pipe continue to move forward and begin to impact the concrete block. As the pipe moves diagonally through the concrete block, it impacts the ‘rebar-near’ and completely rips it apart and in two pieces as major portion of beam elements fail. A bit later, the pipe contacts the ‘rebar -far’ and after passing though it exits out of the concrete block. The damage to ‘rebar-far’ is quite extensive, i.e., roughly 95% element in the middle, all along the width of the ‘rebar-far’ fail. Only a small number of elements at one side of ‘rebar-far’ survive the steel pipe impact. Upon exit from the concrete block, extensive concrete damage is observed on the back side of the concrete block. The simulation results suggest concrete block suffers extensive damage with ‘rebar-near’ failing completely while ‘rebar-far’ suffers near complete failure. The concrete block and the internal components do not survive this slanting pipe missile impact.

COMPARISON OF RESULTS

The damage to the concrete block by the two types of high energy pipe missile impacts can be imagined by looking at the steel pipe central node maximum displacements comparison as a function of time in X-Z plane as shown in figure 3 below.

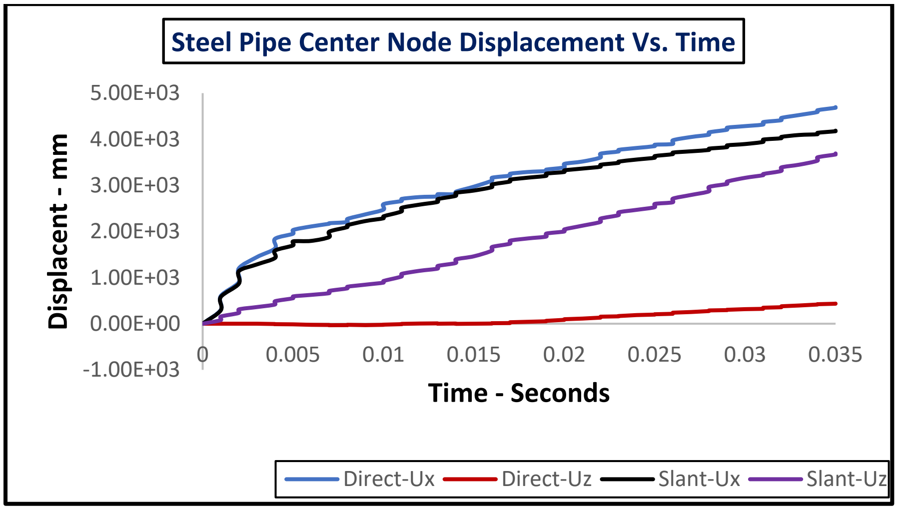

Figure 3. Steel pipe displacements comparison

The pipe central node lies in the middle of the steel pipe along its length and facing the concrete block. For the direct impact, the pipe moves across the concrete block (2000 mm) in around 10 milli seconds. The graph shows that during direct impact the steel pipe moves in X direction only as the Z displacement (Direct-Uz) is extremely small. The steel pipe X displacement for slanting impact is similar. In the Z direction, the pipe central node reaches the side of the block in roughly 20 milli seconds and the steel pipe continues its motion in free space afterwards. The results suggest that during both types of impact, the steel pipes moves though the concrete block completely.

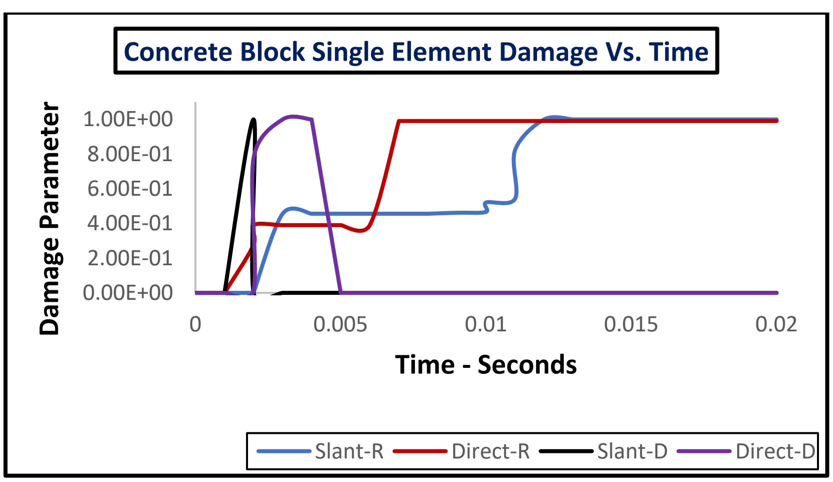

Figure 4. Progression of damage in concrete block (survived material)

Figure 4 shows progression of damage in the concrete containment block on individual element basis. The figure shows that during slanting impact, the first element to reach its failure criterion and subsequently being deleted (Slant-D vs. Direct-D) from solution is sooner than that of direct impact. For the elements which remained, the damage progression is sooner and quicker for direct impact than the slanting impact (Direct-R Vs Slant-R).

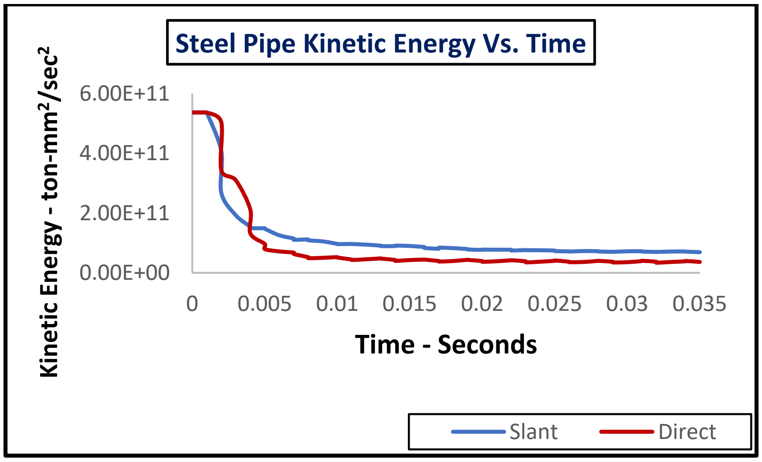

Figure 5. Steel pipe kinetic energy comparison

Figure 5 shows steel pipe kinetic energy for two impact analysis types. The decay in kinetic energy trend is similar. In the initial stages of simulations, the rate of kinetic energy drop is faster for slanting impact than direct impact. For direct impact, the two distinct energy drops represent contact with concrete block and the near rebar. For both cases, the steel pipe kinetic energy remains constant after the pipe exits the concrete block at roughly 15 milli seconds.

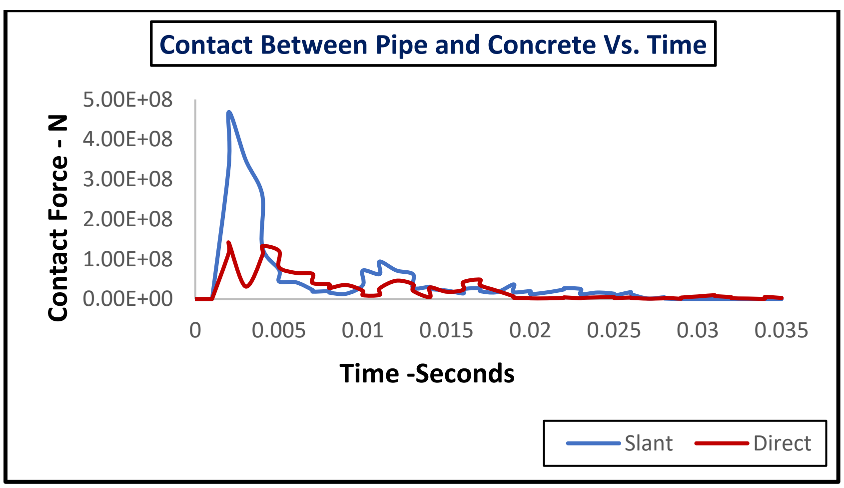

Figure 6. Contact force comparison between steel pipe and concrete block

Figure 6 shows the variation in contact force between the steel pipe and the concrete block. It is apparent that the slanting impact contacts the concrete with much larger force than the direct impact. For a similar starting kinetic energy, it is attributed to the smaller initial contact area for slanting impact as opposed to a much larger area resisting the steel pipe motion for direct impact. Although the steel pipe exits the concrete block by 15 milli seconds, the continued small magnitude contact between steel pipe and concrete suggests impact between disintegrating smaller concrete containment block components and the steel pipe.

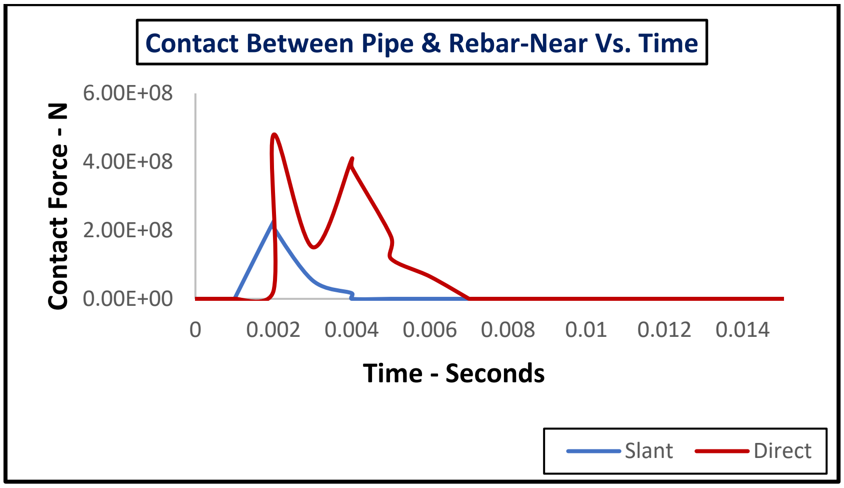

Figure 7. Contact force comparison between steel pipe and rebar-near

Figure 7 shows the contact force developed between the steel pipe and the near rebar. The figure shows that for slanting impact, the contact force begins to develop sooner than that for direct impact. However, the magnitude peak is reached at the same time for the two impacts suggesting a severe impact (i.e., twice the magnitude) with the rebar for the direct impact case. Also, the duration of contact is much longer for the direct impact case. The change in contact force magnitude for direct impact case suggest the steel pipe contact with rebar easing and then re-engaging and finally the contact breaking off completely around 8 milli seconds.

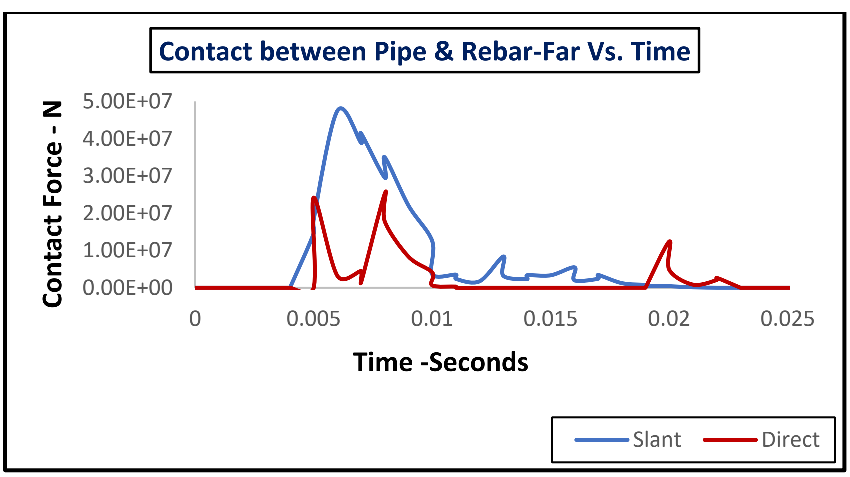

Figure 8. Steel pipe kinetic energy comparison

Figure 8 shows the contact force developed between the steel pipe and the far rebar. The figure shows that for slanting impact, the contact force magnitude is twice as high than that of direct impact. For the direct impact case, the contact is along the rebar width (bending and stretching) whereas for the slanting impact, the steel pipe shears through the far rebar because of the angled/slanted impact. The duration of impact is also slightly larger for slanting impact case. For the direct impact case, it is observed that contacts breaks and re-engages as observed for the near rebar before. The observed rebar deformation behaviour suggest severe bending and stretching of rebar beams under impact resulting in failure of the rebar beams. The impact force re-developing around 20 milli seconds suggest contact between disintegrated rebar portion with the steel pipe.

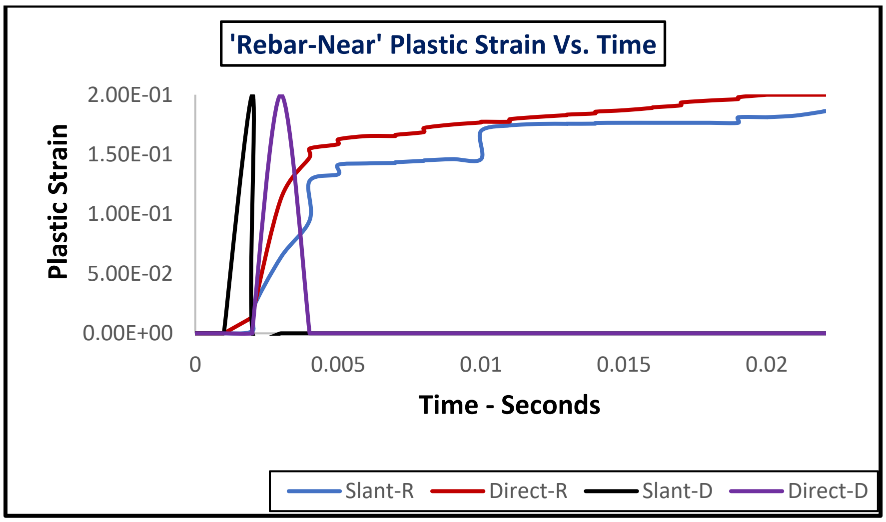

Figure 9. Plastic Strain comparison for ‘rebar-near’

Figure 9 shows accumulation of plastic strain in the near rebar beams, on individual element basis, for the two impact types. The figure shows that during slanting impact, the first element to reach its failure criterion and subsequently being deleted (Slant-D vs. Direct-D) from solution is sooner than that for direct impact. This has also been observed in the case of damage to concrete block elements as well. The element failure is rather quick for slanting impact than for direct impact case. For the elements which did not reach failure criterion and remained in the solution, the plastic strain accumulation is almost similar for the direct impact and the slanting impact (Direct-R Vs Slant-R).

Figure 10 shows accumulation of plastic strain in the far rebar beams, on individual element basis, for the two impact types. As expected, the first element failures are translated in time, from 2 milli seconds to 5 milli seconds, for the two impact cases as compared to near rebar beams. The figure shows that during slanting impact, the first element to reach its failure is sooner than that of direct impact and quicker than the direct impact case. For the elements which did not reach failure criterion and remained in the solution, the plastic strain accumulation is gradual for direct impact case. The plastic strain accumulation is somewhat delayed but with a step increase for the slanting impact case (Direct-R Vs Slant-R).

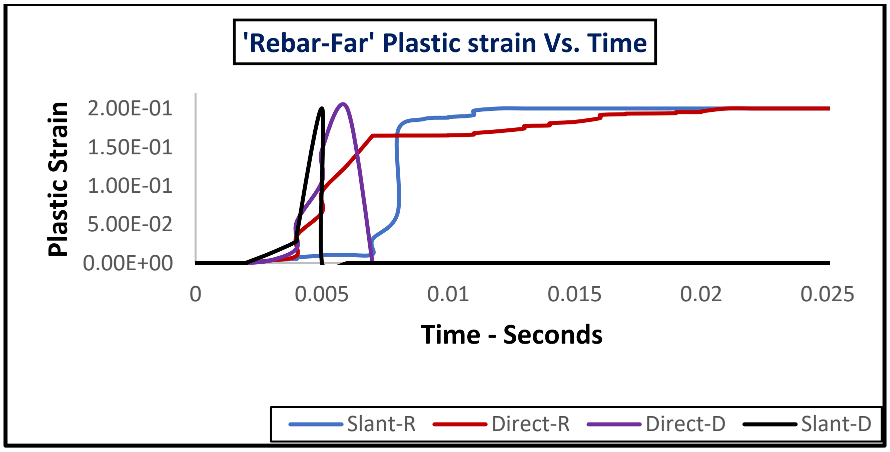

Figure 10. Plastic Strain comparison for 'rebar-far'

CONCLUSIONS

Based on the loads, material properties and the foregoing presentation/discussion of analyses results, following conclusions can be drawn:

- The concrete block representing the reactor containment structure, fails completely with severe damage/material erosion under the action of both direct and slanting steel pipe missile impacts. The steel pipe missile completely penetrated through the concrete block in both type of impacts.
- Both front and rear rebar steel meshes failed with extensive damage and could not stop the steel pipe missile from penetrating through.
- The double rebar design and its placement in the concrete block is in-adequate for containment boundary protection against high energy steel pipe missile impacts considered in this paper.
- 15degrees slanting missile impact is almost as damaging for the concrete containment block as the frontal missile impact.

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