Experimental and numerical study on the orthogonal and oblique impact on water-filled pipes

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**Abstract**

A 300 mm long piece of copper (ASTM B280) pipe with an outer diameter of 35 mm and 0.7 mm wall thickness was subjected to a rigid steel pipe impact under a drop weight loading configuration where the pipe was simply supported at its ends. Differences in deformation features for a pipe subjected to water and an empty pipe were investigated for two configurations namely orthogonal and oblique impact. Compared to orthogonal pipe impact the oblique pipe impact has not been reported in the literature. It is hoped that current work would serve as a first step in this direction. Finite Element Method coupled with Smooth Particle Hydrodynamics (SPH) available in LS-DYNA was used to simulate the empty and water filled pipe impacts under orthogonal and oblique configurations respectively. Fluid structure interaction (FSI) during the water filled pipe impact was successfully modeled using SPH which is a simple method for predicting the short duration FSI events. Experimental results of the effect of varying D/T ratio on the empty and water filled pipes have been reported.

**1. Introduction**

Nuclear Power Plants (NPP) are designed with utmost care for normal operations as well as for the probable accidents that may occur due to earthquake loads [1] on the plant components. Fluid carrying piping is an essential part of NPPs that might be subjected to pipe whip events when pressurized fluid happens to escape a broken or cracked pipe or tubing. To ensure the safety of fluid carrying pipes investigations through experimental testing, analytical procedures or numerical analysis are employed. Piping restraints are an industry standard procedure to restrict the broken pipes from whipping against the neighboring pipes and other structures. An exception may be possible when an NPP operator might request an exemption [2] from using those restraints because during maintenance work the restraints pose an obstruction to the easy access to plant components. Numerous investigations [6–10,12,16] have been carried out by many researchers in the field of pipe whipping. Only a fraction of them which are more directly related to the present work would be briefly discussed in the subsequent sections of this report.

An appreciable number of attempts have been made in terms of testing and finite element analysis to understand the damage or failure caused due to pipe whipping. In an early research work [3] the capabilities of two software packages PALUA and FRUSTA were compared to analyze the 2D and 3D nonlinear pipe whip phenomena due to seismic loading on piping in NPP.

Failure bending moment of a straight pipe is shown to be dependent upon its outer diameter to pipe thickness ratio and the ratio of ultimate tensile strength to yield strength of the pipe material [4]. The bending failure of circumferentially cracked pipes was studied [5]. Flattening may be described by four plastic hinges and is caused by the vertical component of the axially directed bending stresses. An analytical expression for the failure moment of a material subject to strain hardening is presented. Deformation modes of a long missile pipe impacting on a rigid target pipe were explored [6] and it was found that the maximum force of interaction between two pipes cannot be predicted. This is because of the dynamic behavior of the overhanging pipe that depends on a complex interaction of several parameters. A simplified numerical procedure was suggested to estimate the maximum force of interaction. Step by step incremental solution of nonlinear equations of motion was presented using finite element program ADINA [7] to solve the pipe whip problem. Valuable suggestions in terms of FEA usage were made.

Addressing the nuclear power plant safety issues, effect of jet impingement loads and pipe on pipe impact were investigated [8]. In pipe whip incident the collapse mechanism was discussed and multiple modeling approach was recommended. Difference in local and structural pipe collapse was identified. Safety assessment for
the pipe rupture of the primary coolant circuit in nuclear power plants was performed by conducting a series of pipe whip tests and finite element analysis [9]. The development of a finite element code is described [10] that was able to predict the pipe deformation resulting from pipe whip when the pipe was filled with water. FSI is predicted using the computer code. This study is closely related to the present work where effect of water filled pipe has been considered but the problem studied could focus only on global pipe motion and the code’s importance at the time of its application had been quite successful but in our studies we have used a very sophisticated code (LS-DYNA) which is able to predict local deformation in the pipe precisely.

An extensive study was conducted by [11] to recommend energy absorbing systems for pipe whip restraints. Though the technique considered was applicable to numerous situations in structural design the emphasis was on the pipe whipping subject. Pipe on pipe impact (p-o-p-i) was investigated [12] to determine the crucial length of missile pipe that might cause severe damage to the target pipe. Due to the complex nature of pipe on pipe impact it was not possible to obtain a damage model but the authors were able to simulate the impact event using LS-DYNA quite successfully.

An interesting study by [13] was conducted on the behavior of a whipping pipe that was pressurized to a certain extent and subsequently the fluid was released which rotated the specially built missile pipe instantly about its fixed end. The focus in this study was on the deformation modes of the missile pipe. Stress corrosion cracks were discovered in a Group Distribution Header (GDH) at the Ignalina NPP and also in the GDHs at the Chernobyl NPP, therefore the possibility of a guillotine pipe break is possible. The consequences of this type of structural failure would be to propel the failed GDH, potentially into adjacent GDHs or walls. Finite element analysis was conducted to predict the extent of expected damage [14].
Empty and water filled mild steel pipes were impact tested when water filled pipes were pressurized using steel billets and sections of steel pipe projectiles at velocities ranging from 46 to 325 m s\(^{-1}\) [16]. The oval dent size of water filled pipes was noted to be smaller in size when compared to empty pipes. Perforation of water filled pipes was found to be more likely. Empty pipes had shown compressive hoop strains while water filled pipes displayed tensile hoop strains. Lateral impacts on fully clamped mild steel pipes were carried out for various diameters to wall thickness ratios. The extensive study on 130 pipe specimens generated a good amount of useful data that was envisaged to help in the design.

![Fig. 6. Water filled target pipe orientation for oblique (37\(^{\circ}\)) impact test.](image)

Table 1

<table>
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<tr>
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<th>PR</th>
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</table>

![Fig. 7. Finite element model of pipe impact test in LS-DYNA.](image)
Fig. 8. Axial and transverse cross sections of water filled pipe after orthogonal impact. Dent Width and diameter change are shown.

process. The studies also found that the laws of geometrically similar scaling were almost satisfied over a scale range of five [17].

Similar studies as in [17] were carried out by [18] on 226 fully clamped pipe specimens. The objective of the investigation was to achieve various failure modes so that appropriate pipe failure

<table>
<thead>
<tr>
<th>Specimen number</th>
<th>Dent width, h (mm)</th>
<th>Reduced diameter, h (mm)</th>
<th>Reduced (inner) diameter, h (mm)</th>
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<td>11.2</td>
</tr>
<tr>
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</tr>
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<td>15.0</td>
<td>12.8</td>
</tr>
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<td>27.6</td>
<td>14.5</td>
<td>12.2</td>
</tr>
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<td>11.8</td>
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<td>15.8</td>
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</table>

Table 3

Dent width and diameter variation of a copper pipe impacted orthogonally (90°) for a diameter to the wall thickness ratio of approximately 32. D/t = 22.2/0.7 = 31.74.

From the above mentioned research works conducted by various authors [1–14,17–21] it is evident that there have been rather fewer [16] number of studies where the damage or failure of water filled target pipes have been sought. Empty target pipe impact was investigated in [12] and the deformation modes were studied but the same was not done for water filled target pipes. From [10] it is evident that an early computer code was able to identify the global movement of a whipping pipe (missile pipe) but there has been no mention regarding the local deformation of a water filled target pipe. This may be due to the complexity of the problem that though the experimental work has been extensive the finite element simulations for the situation at hand have been rare.

In the present work the pipe impact has been investigated using experimental testing and subsequently predictions of structural damage caused due to impact loading have been simulated using LS-DYNA. In the present work the main focus has been on the water filled target pipe being impacted by a rigid pipe. LS-DYNA with its SPH capabilities has been able to validate the experimental work reliably. The objective of the present project was to study the damage of water filled pipes and compare the amount of damage to the damage of empty pipes and explore to what extent the water filled target pipes are safer. The other objective was to determine the suitability of smooth particle hydrodynamics to model FSI.

2. Experimental work

A few samples of the copper target pipes selected for impact testing are shown in Fig. 1. A 300 mm long copper (ASTM B280) pipe with an outer diameter of 35 mm and a 0.7 mm of wall
thickness was subjected to a steel missile pipe (diameter = 27.3 mm, wall thickness = 2.65 mm) impact by dropping a cylindrical weight of 4.63 kg mass through a vertical pipe on the steel pipe (missile pipe) from a height of 2.275 m gaining a velocity of 6.71 ms$^{-1}$ at the point of impact. An additional 4 kg steel mass was welded to the end of steel pipe for an added damage of the target pipe. Fig. 2 shows the configuration of water filled pipe where two flexible rubber caps were used to hold the water inside the pipe. Two 2.4 mm thick rubber caps were used to secure both ends of the copper pipe specimens tightly. It was assured that the rubber caps were firmly held onto the pipe ends and the water did not leak after impact.

Fig. 3 shows the experimental rig with missile and target pipes. The two ends of the target pipe were simply supported on a frame as shown in the photograph in Fig. 6 so that it would be secured lightly on the frame but it is free to bend and rotate under impact loading. Fig. 6 is a closer view of Fig. 3 where the missile pipe is held directly on the top of target pipe before falling weight impacts upon the missile pipe. Missile pipe is made up of steel with an outer diameter of 27.3 mm and a wall thickness of 2.65 mm so that the missile pipe would behave as a rigid body with negligible damage under impact loads used during this work. The impacting pipe was placed on the target pipe in direct contact before impact.

Two configurations for the pipe impact were considered namely orthogonal and oblique impact. The test orientation of falling weight, missile pipe, and the target pipe is shown more clearly in Fig. 7 for both cases.

As the aim of this study was not to deform the sample pipes to failure but to be able to compare the damage caused due to a constant load when the pipes were filled with water or when they

Fig. 9. A sample of dent width measurement after orthogonal and oblique pipe impact.

Fig. 10. Dent width and diameter change after orthogonal (90°) impact for empty and water filled pipes.
were empty. A falling mass was selected that can cause a predetermined amount of damage to the target pipe. Subsequently same falling mass was used in all the experiments.

Fig. 4 shows four samples of empty and water filled (two for each case) copper pipes after impact testing under orthogonal (90°) pipe impact. Though most of the pipe to pipe impact research work [1–21] has been carried out under orthogonal impact conditions the actual impact in the field can happen at any angle depending upon the orientations of missile and target pipes at the instant of impact. To have a better understanding of such impact conditions oblique impact tests were also carried out in the present investigations. In Fig. 5 similar dimension pipes as mentioned above are shown after oblique (37°) impact. The oblique impact orientation is shown in Fig. 6 photograph. Same structure was used to carry out orthogonal impact on the copper pipe. Close observation of Figs. 4 and 5 reveals that the oval shaped dent size [16] resulting from impact tests for empty pipes impacted with the same mass is larger for orthogonal and oblique impacts when compared to the water filled pipe dent sizes. The steel missile pipe behaves like a cantilever beam and the overhanging length of the missile pipe was shorter when it struck the obliquely oriented target pipe. The falling weight in all tests (orthogonal and oblique) was same.

Though the falling mass in all tests was kept constant, the resulting target pipe deformation for orthogonal and oblique impact tests cannot be compared directly to each other because of the different amount of moment experienced in both cases owing to the different overhanging length of the missile pipe and different contact area in two cases. The comparison was therefore made between deformations occurring in empty and water filled pipes separately.

Fig. 6 shows the test case of water filled pipe subjected to oblique impact.

As shown in Figs. 4 and 5, and Fig. 13 the dent size was measured along the cross section of the pipe where the diameter of the pipe has increased and it was defined as dent size. For the oblique damage the dent size was considered to be along the oblique deformed path. The dent size obtained from oblique impact is

![Graph showing dent width and diameter change after oblique impact for empty and water filled pipes.](image1)

![Graph showing energy absorbed by empty and water filled pipes under orthogonal and oblique impacts.](image2)

![Graph showing diameter for empty and water filled pipes under oblique impact.](image3)

**Fig. 11.** Dent width and diameter change after oblique (37°) impact for empty and water filled pipes.

**Fig. 12.** Energy absorbed by empty and water filled pipes under orthogonal and oblique impacts.

**Fig. 13.** A sample pipe section for a D/T ratio of 32 after impact. Dent Width = b, Reduced diameter = h.
larger as the dent covers more area on the pipe surface. Dent size measurement sample for orthogonal and oblique impact is also shown in Fig. 9 obtained from FEA. The other parameter studied for comparison was the reduction in the diameter of target pipe after impact. The two parameters investigated (dent size and diameter reduction) are defined in Figs. 8 and 13.

In the above mentioned work 300 mm long copper pipes with D/T ratio of 50 were used which showed difference in empty and water filled pipe deformations upon impact. In an additional work which has not been mentioned here in detail the copper pipes of 300 mm length and a D/T ratio of 32 were impact tested under similar conditions for empty and water filled configurations and no difference in pipe deformations was observed for the two cases. Fig. 13 and Table 3 briefly show the results.

3. Numerical analysis

The above mentioned experimental work was modeled in LS-DYNA using 4-Node shell elements for the missile and target pipes as shown in Fig. 7. An isometric view of the falling weight, two supports for the target pipe, missile pipe and the target pipe are shown in the first view in the figure. Top view of two impact configurations namely the orthogonal (90°) and oblique (37°) impact adapted from experimental work are also shown in the figure.

Target pipe supports were also modeled with shell elements while the falling cylindrical mass was modeled with solid elements (rigid parts). Target pipe ends were constrained along the missile pipe axis to represent the physical constraints shown in Fig. 6. The welded mass at the end of missile pipe was modeled by a mass node with a 4 kg mass. The near end of the missile pipe is free to rotate about its fixed end and the falling mass has a velocity of 6.71 ms⁻¹ at the point of impact.

Gravity load of 9.8 ms⁻² is applied to the whole FEA model. A sufficiently refined mesh of 0.96 mm for the target pipe was used. The contact between two pipes has been defined as Contact Automatic Surface to surface. Target pipe material was modeled using Johnson_Cook material model with the material properties as shown in Table 1 [15]. No Equation of State (EOS) is required as the target pipe was meshed with shell elements. The EOS is required for deformable solid elements because it represents the relationship between pressure and volume of the deforming structure. Units adapted in this simulation work are milliseconds, GPa, kN and kg.

In finite element results the pipe thickness was modeled with shell elements therefore the diameter measurements were based upon the "through the thickness" midpoint of the shell elements. Therefore the target pipe diameter in FEA was 34.65 mm instead of 35.00 mm owing to the fact that the pipe thickness was 0.7 mm. All the distances between different interacting parts were offset accordingly.

The rubber caps at the end of the water filled pipes were not modeled as rubber material but as copper ends. The reason for this is that the influence of the pipe ends at the localized deformation at the mid span of the pipe during impact is insignificant although it is very simple to model it by assigning it rubber properties if necessary. Impact events take place in few milliseconds therefore the pipe ends that are located sufficiently away from the impact

Fig. 14. (a) Maximum stress in the empty pipe subjected to orthogonal impact = 288 MPa at time 10 ms. (b) Maximum stress in the water filled pipe subjected to orthogonal impact = 304 MPa at time 10 ms.
location play little role in localized deformation process and are therefore not required to be modeled in detail.

4. Smooth particle hydrodynamics (SPH)

Smooth Particle Hydrodynamics (SPH) is a comparatively new technique that is being used to perform simulations of varied nature physical phenomena. Examples that can be cited are like metal cutting [22,23] and fuel tank sloshing [24]. Smooth Particle Hydrodynamics (SPH) available in LS-DYNA can be seamlessly coupled with Finite Element Analysis, therefore FSI investigation is made simple by using SPH technique. In the present study the water filled pipes under orthogonal and oblique impact conditions were modeled using SPH particles and the material model used was MAT_NULL with GRUNEISEN EOS. Water density used was 1.0E-6 kg/mm³. Speed of sound in water was considered as 1483 mm/ms. No other parameters are required for simple SPH analysis.

The contact between water (SPH particles) and target pipe (shell elements) was defined as Contact Automatic Nodes to Surface. Fig. 8 shows the axial and transverse cross sections for water filled pipe to expose the water particles in the pipe after impact. Pipe dent width and diameter change parameters resulting from the impact are also defined in the figure. Sufficient particle density (1 mm in x, y, and z directions in the current analysis) was used so that a thorough contact between the water particles and the pipe wall could be established. Moreover as a rule of thumb the when shell elements come into contact with SPH particles the particle density has to be larger than the shell element size so that the SPH particles do not leak through the shell wall. The experience also shows that when the SPH particle density is insufficient the gravity loading causes the particles to squeeze in gravity loading direction and this may increase the error due to lack of contact between the particles (water) and the structure (pipe). Increased number of particles demands higher computational time and resources. Therefore a compromise has to be struck between precision and a reasonably precise engineering solution.

5. Results and discussion

Detailed experimental results are shown in Table 2 where the effect of water filled pipes on their deformation pertaining to dent width and diameter change is compared to the results obtained from empty pipe impacts.

Fig. 10 and Fig. 11 show the dent width and diameter changes of empty and water filled pipes. Oval dent width for water filled pipe under orthogonal impact is compared to the dent width for empty pipe in Fig. 10. In the figure zero stands for an empty pipe while 100 stands for filled pipe. The experimental and simulation results can be seen in very good agreement. The reduction in diameter due to impact can also be viewed in Fig. 10 and the results
for both cases that is empty and water filled pipe are precisely same which is very encouraging.

In Fig. 11 the dent width and the diameter reduction of the target pipe after impact for oblique impact is compared. Dent width data in this figure again shows a very good match. Diameter reduction in case of oblique impact shows some difference but overall trend is yet in good agreement with experimental work. Fig. 12 shows the energy absorbed by the empty and water filled pipes subjected to impact. The energy absorbed by the water filled pipes is divided into two portions where a small amount of energy is absorbed by water and the large part is absorbed by the copper pipe. The energy absorbed stabilizes after about 6 ms.

The LS-DYNA results in all the cases are in close agreement with the experimental results though some small discrepancies are evident which can be overcome with further investigations. The pipe diameter to wall thickness ratio in the present work was kept at 50. Under a separate set of experiments shown in Fig. 13 and Table 3 this ratio was kept at 32 in which case the deformation of empty and water filled pipes had shown no significant difference in deformations. This means that when the D/T ratio is below a certain threshold value the variations in diameter and dent width remain insensitive to empty or water filled conditions. This is proposed be investigated in a future work.

Fig. 14(a) shows the maximum stress at the plastic hinge of the pipe subjected to orthogonal impact for empty pipe while Fig. 14(b) shows the maximum stress for the water filled pipe. In case of empty pipe the maximum stress generated at the plastic hinge at 10 ms was 288 MPa while the maximum stress for water filled pipe at the same location was recorded to be 304 MPa. In Fig. 15(a) and (b) the maximum stresses for empty and water filled pipes are shown under oblique impact conditions. Empty pipe shows a maximum stress of 290 MPa and the water filled pipe undergoes a maximum stress of 306 MPa at 8.44 ms.

Though the deformation of water filled pipes is smaller when compared to the empty pipes the stresses experienced by the deforming pipes at the hinge location are higher because of internal water pressure in the pipe and therefore the water filled pipes are more vulnerable to damage and failure [16].

6. Conclusions

Empty and water filled copper pipes were subjected to orthogonal and oblique drop weight loading to assess the difference in deformation modes of the copper pipes. Finite element simulations using smooth particle hydrodynamics were utilized to simulate the water filled pipe impact event. Following conclusions were made.

Although the pipe deformations in the water filled pipes is smaller when compared to the empty pipes subjected to orthogonal and oblique impacts the stresses generated in the water filled pipes are higher which makes the water filled pipes more vulnerable to higher damage and failure [16].

Smooth particle hydrodynamics coupled with FEA can be used to investigate the deformations of the water filled pipes and other liquid filled containers under hydrocodes like LS-DYNA. In pipe on pipe impact scenarios fluids can easily be represented using particles instead of solid elements because solid elements subjected to large deformations using lagrangian formulation prove to be inefficient.

Below a certain D/T ratio the pipe deformations caused due to lateral impact remain insensitive to empty or water filled conditions.

The deformation pattern in empty and water filled pipes subjected to orthogonal and oblique impacts show similar behavior and the stresses experienced in both cases are approximately same.

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References