WIND-BORNE MISSILE IMPACT ON REINFORCED CONCRETE NUCLEAR STRUCTURES: A PARAMETRIC STUDY

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ABSTRACT

A parametric study was conducted to investigate the effects of panel thickness, Schedule 40 pipe size (mass and diameter), pipe velocity, and concrete uniaxial compressive and tensile strength on the resistance of reinforced concrete panels to impact by wind-borne missiles. The axisymmetric SPH model used for the simulations was partially validated using data from tests of four reinforced concrete panels. The values of panel thickness and concrete compressive strengths considered in the parametric study are typical of those in existing nuclear power plant structures in the United States. The impact velocities envelope the maximum velocities recommended by U.S. NRC Regulatory Guides 1.76 (=41 m/s) and 1.221 (=94 m/s) for the design against the impact of Schedule 40 pipes. Impact resistance was evaluated using the metrics of a) perforation (complete penetration of the panel by the missile), and b) scabbing (ejection) of concrete from the back face. A considerable number of design parameters have a meaningful effect on the impact resistance of reinforced concrete panels. The most important parameter, aside from panel thickness, is tensile strength of concrete.

INTRODUCTION

Containment structures in nuclear power plants (NPPs) are designed to remain intact under the effects of rare earthquake shaking and severe meteorological events, including tornado and/or hurricane winds and missiles borne by those winds. Wind-borne objects can pose a serious threat to walls and roofs of nuclear power plants because these objects may penetrate or perforate panels, causing unpredictable damage to structures, systems and components inside containment.

Empirical formulate for normal (90°) impact have traditionally been used in the design of nuclear facilities against the effects of hurricane- and tornado-borne missiles. These formulae categorize response by 1) missile penetration depth, 2) panel thickness required to prevent scabbing (ejection of fragments from the back, non-impact, face of the panel), and 3) panel thickness to prevent perforation (complete penetration of the missile through the panel). The reliability of these empirical equations is questionable because they were formulated from high-speed (152-610 m/sec) impact tests of non-deformable missiles designed to penetrate (Kennedy, 1975). Design velocities for wind-borne missile impact on nuclear facilities are substantially smaller than 152-610 m/sec and these missiles are typically blunt ended and deformable. Such missiles are expected to absorb some of the energy of the impact, reducing local damage. Terranova et al. (2015) evaluated the applicability of the empirical formulae for wind-borne missile impact by comparing predictions to a limited number of physical tests involving wooden utility poles, steel pipes and rods conducted by EPRI and Calspan in the 1970s (Stephenson, 1977; Vassallo, 1975). That study concluded that the empirical formulae do not inspire the level of confidence expected for the analysis and design of a nuclear power plant structure. The shortcomings with the predictive equations, and a lack of knowledge regarding those parameters that most affect impact resistance against soft and hard missiles, prompted the authors to validate a numerical tool for impact analysis of reinforced concrete panels. Such a model could then be used to develop improved predictive equations for design.

Tu and Murray (1977) used the finite element method to examine impact of tornado-borne missiles on reinforced concrete panels. Their study simulated the impact of an 8-inch diameter steel slug and a 12-inch diameter Schedule 40 pipe and used the scabbing data for model validation; penetration depths and conical plug sizes were not reported. The study did not provide sufficient information for a detailed review of the numerical models and solution algorithms. Terranova et al. (2015) simulated the impact of a 12-inch (305 mm) diameter Schedule 40 pipe onto a 12-inch (305 mm) thick reinforced concrete panel using the Lagrangian and the Smooth Particle Hydrodynamics (SPH) methods. The numerical models predicted the local damage to the panel with reasonable accuracy. The numerical studies conducted by Tu and Murray (1977) and Terranova et al. (2015) were limited in scope.

Terranova et al. (2016) simulated four impact tests of concrete panels conducted by EPRI to validate, in part, a numerical model using LS-DYNA (LSTC, 2012). These tests involved 12 in (305 mm), 18 in (460 mm) and 24 in (610 mm) thick reinforced concrete panels impacted by 12-inch (305 mm) diameter Schedule 40 pipes with impact velocities ranging from 98 fps (30 m/s) to 202 fps (62 m/s). An axisymmetric SPH formulation was used for these simulations. The numerical model reasonably predicted panel response and damage (e.g., perforation, front and back face crater diameters, and scabbing) for a range of panel thicknesses. The partially validated numerical model was also used in a study of limited scope to investigate the effects of concrete compressive and tensile strength, and solid versus annular missiles, on panel response to impact loadings. Results clearly indicated that all three parameters affect the behavior of a panel.

The numerical model described in Terranova et al. (2016) is used in a parametric study to investigate the effects of panel thickness, Schedule 40 pipe size (mass and diameter), impact velocity, and concrete compressive and tensile strength on impact resistance. The next section describes the LS-DYNA models and design variables chosen for the parametric study. Preliminary analysis results and findings are presented in the following sections. Detailed information and conclusions are presented in Terranova et al. (2017, 2018).

PARAMETRIC STUDY

The general-purpose finite element code LS-DYNA is used to simulate the response of 153 concrete panels to normal impact of wind-borne missiles. The 6 in (152 mm) diameter Schedule 40 pipe is one of the missiles in a set required to be used by the US Nuclear Regulatory Commission for the design of exterior, above grade, walls and slabs in nuclear power plants, per Regulatory Guides (RG) 1.76 (NRC, 2007) and 1.221 (NRC, 2011). This missile is used in the parametric study.

Design Parameters

A significant number of parameters affect the impact resistance of reinforced concrete panels, including panel thickness, and uniaxial concrete compressive strength and tensile strength. The mass and diameter of the Schedule 40 pipe and the impact velocity also play a significant role in the response of the panel. Panel thicknesses of 12 in (305 mm), 15 in (381 mm), 18 in (460 mm), and 25.6 in (650 mm), typical of walls in nuclear power plants, were investigated. Table 1 identifies the parameters considered and their magnitudes examined in this study, where d is the outer diameter of the Schedule 40 pipe, v is the impact velocity of the pipe, and f_c' and f_t' are the concrete compressive and tensile strengths, respectively. Three magnitudes of each parameter were considered: low, medium, and high. Schedule 40 pipe diameters of 6 in. (152.4 mm), 8 in (203 mm), and 10 in (254 mm) were chosen with mass of 0.74 lb-sec^2/in (130 kg), 1.11 lb-sec^2/in (195 kg), and 1.57 lb-sec^2/in (276 kg), respectively. The masses are based on a 15 ft. (4.58 m) long pipe, which is the length of a 6 inch (152.4 mm) diameter Schedule 40 pipe given in RG 1.76 (2007) and RG 1.221 (2011). Schedule 40 pipes with diameters of 8 in (203.2 mm) and 10 in (254 mm) were included in this study to expand the dataset and the conclusions.

Three magnitudes of impact velocity were investigated: 1575 in/sec (40 m/s), 2756 in/sec (70 m/s), and 3937 in/sec (100 m/s). The chosen velocities envelope the maximum velocities recommended by RG 1.76 (=1620 in/sec (41 m/s)) and RG 1.221 (=3696 in/sec (94 m/s)) for the design of panels to resist impact by Schedule 40 pipes. Concrete compressive strengths of 4351 psi (30 MPa), 5801 psi (40 MPa), and 7251 psi (50 MPa) were examined: enveloping concrete strengths in nuclear power plant structures. Concrete tensile strength also has a significant effect on the impact resistance of reinforced concrete panels as observed in Terranova et al. (2016) and by others. Tensile strengths ranging from 435 psi (3 MPa) to 725 psi (5 MPa) were considered in this study and these are 10% of the compressive strengths for 4351 psi (30 MPa) and 7251 psi (50 MPa) concrete, respectively.

Table 1: Parameters used in parametric study

	Low	Medium	High
d , in (mm)	6 (152)	8 (203)	10 (254)
v , in/sec (m/sec)	1575 (40)	2756 (70)	3937 (100)
f_c' , psi (MPa)	4351 (30)	5801 (40)	7251 (50)
f_t' , psi (MPa)	435 (3)	580 (4)	725 (5)

Since a 12-inch (305 mm) thick panel is more vulnerable to concrete scabbing (e.g., ejection of concrete on the back face) and perforation (complete penetration of the panel) than the 15 in (381 mm), 18 in (460 mm), and 25.6 in (650 mm) thick panels, all 81 combinations of Schedule 40 pipe size, pipe velocity and compressive and tensile strength identified in Table 1 were simulated. For the 15 in (381 mm), 18 in (460 mm), and 25.6 in (650 mm) thick panels, simulations were conducted for each diameter of Schedule 40 pipe (e.g., 6 in (152 mm), 8 in (203 mm), and 10 in (254 mm)) for each panel thickness. Simulations were performed for the low and high values of projectile velocity and concrete compressive and tensile strength identified in Table 1 for each pipe diameter. A complete list of simulations (total of 153) is presented in Terranova et al. (2017, 2018).

LS-DYNA Models used for the Parametric Study

The axisymmetric model of the 12 in (305 mm) thick panel is shown in Figure 1; the axisymmetric models of the 15 in (381 mm), 18 in (460 mm) and 25.6 in (650 mm) thick panels were similar and are not shown here. Twelve models were used in the simulations; three pipe sizes for each panel thickness. SPH particles were used for the concrete panels and pipes. A concrete particle spacing of 0.08 in (2 mm) was used for the 12 in (305 mm), 15 in (381 mm), and 18 in (460 mm) thick panels. A 0.12 in (3 mm) spacing was adopted for the 25.6 in (650 mm) thick panel. The mesh size for each panel thickness was based on mesh sensitivity studies presented in Terranova et al. (2017, 2018) for the 12 in (305 mm), 18 in (460 mm), and 24 in (610 mm) thick panels. The spacing of the pipe particles was set equal to one half that of the spacing of the concrete particles to ensure that each particle had the same mass.

The material model MAT072R3 in LS-DYNA was used for the concrete because it recovered the results of the EPRI experiments with reasonable accuracy (Terranova et al., 2016). The Dynamic Increase Factors for strain-rate effects in concrete follow the CEB formulation (CEB/FIP, 1990) in compression and the Hao and Zhou formulation in tension (see Dusenberry, 2010). The Johnson-Cook (JC) material model (MAT015) was used for the Schedule 40 pipe, with yield strength set equal to 73 ksi (503 MPa). The Borvik et al. (2004) JC material parameters for 71 ksi (490 MPa) steel were used. The equation of state keyword EOS_LINEAR_POLYNOMIAL was activated for the JC material model by setting the variable C1 equal to the bulk modulus of steel (=2.3 $\times 10^7$ psi (1.6 $\times 10^5$ MPa)).

The default particle approximation theory (ELFORM=0 in LS-DYNA) was used for the SPH particles. Monaghan-type artificial viscosity was activated by setting the variable IAVIS to zero in the *CONTROL_SPH keyword, which is required for axisymmetric simulations. Variables Q1 and Q2 were set equal to one in the *CONTROL_BULK_VISCOSITY keyword per Liu et al. (2003). Two columns of SPH particles constrained displacement in the Y-direction on the outer edge of the panel to simulate a pinned boundary condition.

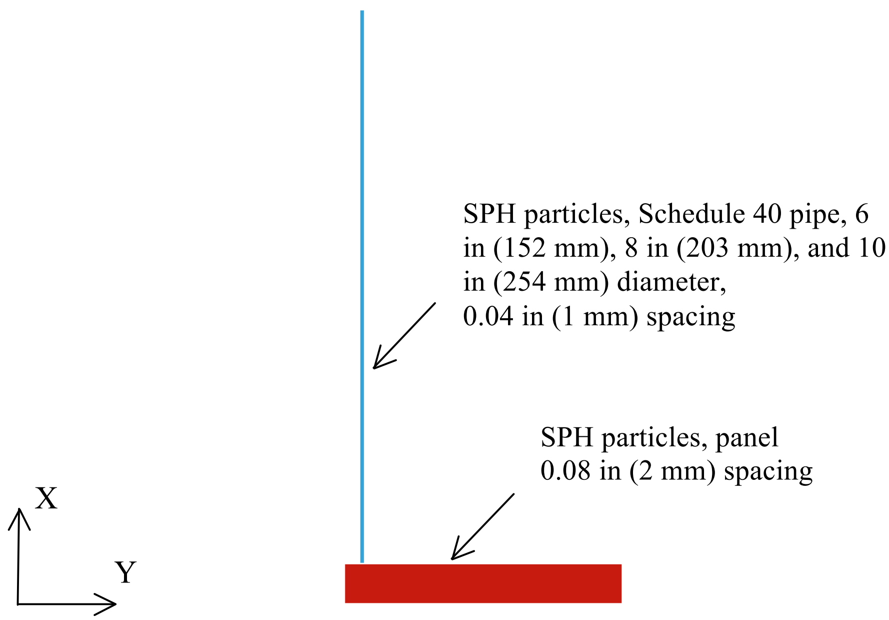
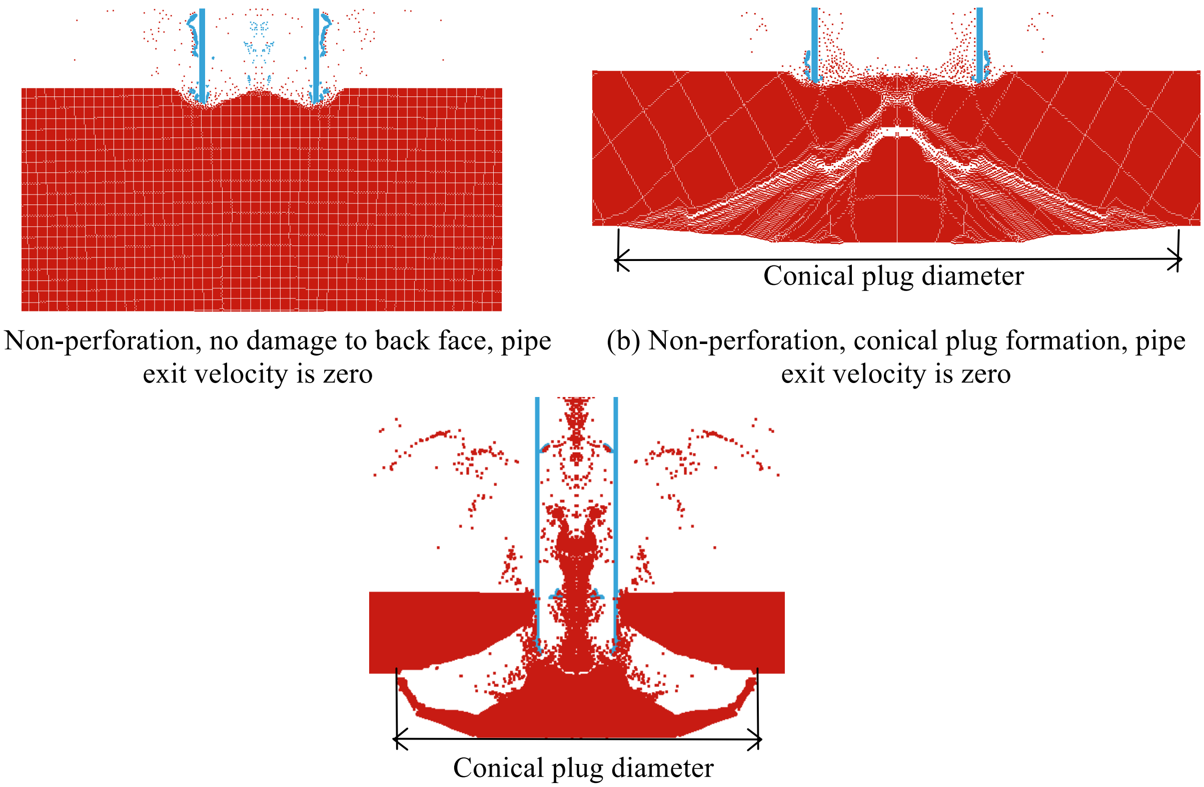


Figure 1: Axisymmetric model of 12-inch (305 mm) thick panel

IMPACT SIMULATION RESULTS

Introduction

The effects on resistance to impact of panel thickness, concrete compressive and tensile strength, pipe mass and diameter, and impact velocity are investigated in this section. Figure 2 presents the terminology used to evaluate the panels. The simulation results are categorized by non-perforation (Figure 2a and Figure 2b) and perforation (Figure 2c) tests. In the non-perforation tests, the pipe does not completely penetrate the panel (i.e., exit velocity of the pipe is zero). Two outcomes of importance are considered in the non-perforation tests: 1) no damage to the back (non-impact) face (Figure 2a), and 2) formation of a conical plug on the back face of the panel (Figure 2b). If the conical plug forms, scabbing (ejection of fragments from the back, non-impact face) of concrete is assumed to occur. (Spalling of concrete from the front or impact face is not of concern because material will not be lost inside the containment.) In the perforation tests, the pipe completely penetrates the panel (i.e., exit velocity is greater than zero) (see Figure 2c). The predicted conical plug diameter for non-perforation and perforation tests is defined in Figures 2b and 2c, respectively.



(a) Non-perforation, no damage to back face, pipe exit velocity is zero

(b) Non-perforation, conical plug formation, pipe exit velocity is zero

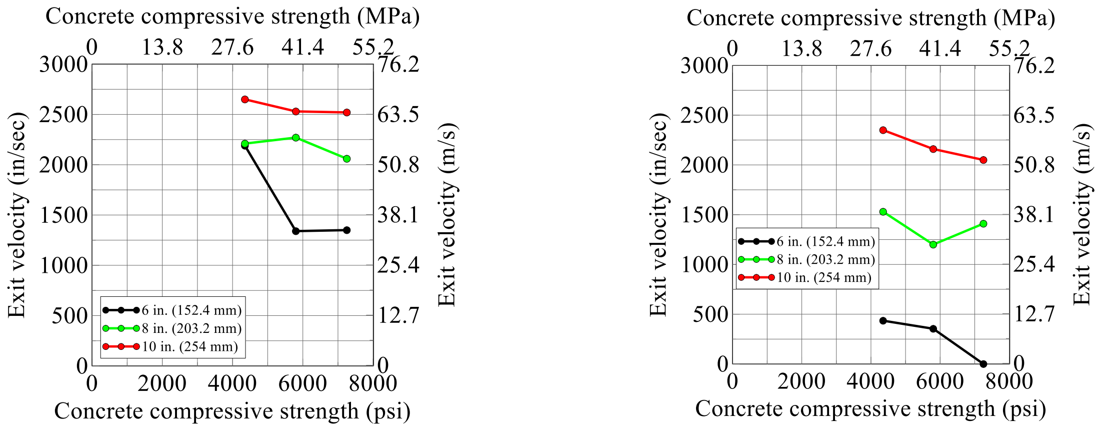
(c) Perforation, pipe exit velocity is nonzero

Figure 2: Terminology used to evaluate panel response

The predicted conical plug diameters and exit velocities for all 153 simulations were tabulated and the results are presented in Terranova et al. (2017, 2018). The following sections present plots of the exit velocity as a function of panel thickness, concrete compressive and tensile strength, pipe velocity and pipe mass and diameter to investigate their influence on impact resistance. The effect of concrete compressive and tensile strength, and Schedule 40 pipe velocity and size on impact resistance are evaluated using results of the 12-inch (305 mm) thick panel because thicker panels are less vulnerable to concrete scabbing and perforation. The effectiveness of a panel to resist pipe impact is based on its ability to prevent a) perforation, and b) scabbing of concrete on the back face. Limited data are presented here. All of the results are presented in Terranova et al. (2017, 2018).

Concrete Compressive and Tensile Strength

The exit velocity of the Schedule 40 pipe as a function of concrete compressive strength is presented in Figure 3 for 6 in (152 mm), 8 in (203 mm), and 10 in (254 mm) diameter pipes impacting panels at a velocity of 3937 in/sec (100 m/s). Results are shown for concrete tensile strengths of 435 psi (3 MPa) and 725 psi (5 MPa). The results suggest that concrete compressive strength has a relatively small effect on impact resistance.

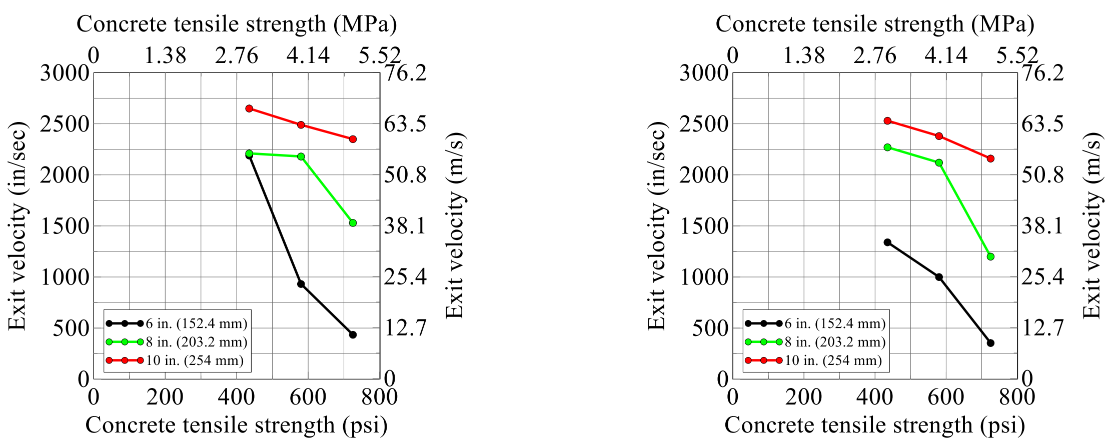


(a) f_t' =435 psi (3 MPa) (b) f_t' =725 psi (5 MPa)

Figure 3: Exit velocity of Schedule 40 pipe as a function of concrete compressive strength, v =3937 in/sec (100 m/sec), 12-inch (305 mm) thick panel

Concrete Tensile and Compressive Strength

The exit velocity of the Schedule 40 pipe as a function of concrete tensile strength is presented in Figure 4 for 6 in (152 mm), 8 in (203 mm), and 10 in (254 mm) diameter pipes normally impacting the 12-inch (305 mm) thick panel at a velocity of 3937 in/sec (100 m/s). Results are presented for concrete compressive strengths of 4351 psi (30 MPa) and 5801 MPa (40 MPa). The exit velocities decrease substantially as tensile strength increases, indicating that this parameter has a very significant effect on the impact resistance of a panel.



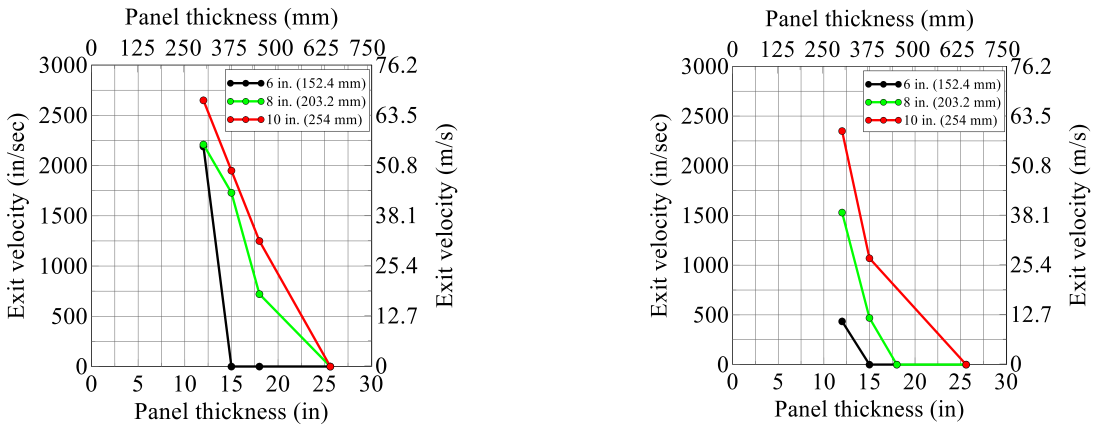
(a) f_c' =4351 psi (30 MPa) (b) f_c' =5801 psi (40 MPa)

Figure 4: Exit velocity of Schedule 40 pipe as a function of concrete tensile strength, v =3937 in/sec (100 m/sec), 12-inch (305 mm) thick panel

Concrete Panel Thickness and Concrete Compressive and Tensile Strength

Figure 5 presents the exit velocity of the Schedule 40 pipe as a function of concrete panel thickness for 6 in (152 mm), 8 in (203 mm), and 10 in (254 mm) diameter pipes normally impacting panels at a velocity of 3937 in/sec (100 m/s). The masses of the 6 in (152 mm), 8 in (203 mm), and 10 in (254 mm) diameter pipes are 0.74 lb-sec^2/in (130 kg), 1.11 lb-sec^2/in (195 kg), and 1.57 lb-sec^2/in (276 kg), respectively. Results are presented for a concrete compressive strength of 4351 psi (30 MPa) and tensile strengths of

435 psi (3 MPa) and 725 psi (5 MPa). The pipe exit velocity decreases as the panel thickness increases, which is an expected result. The 25.6 in (650 mm) thick panels were not perforated (i.e., exit velocity is zero) for all three diameters of pipe.

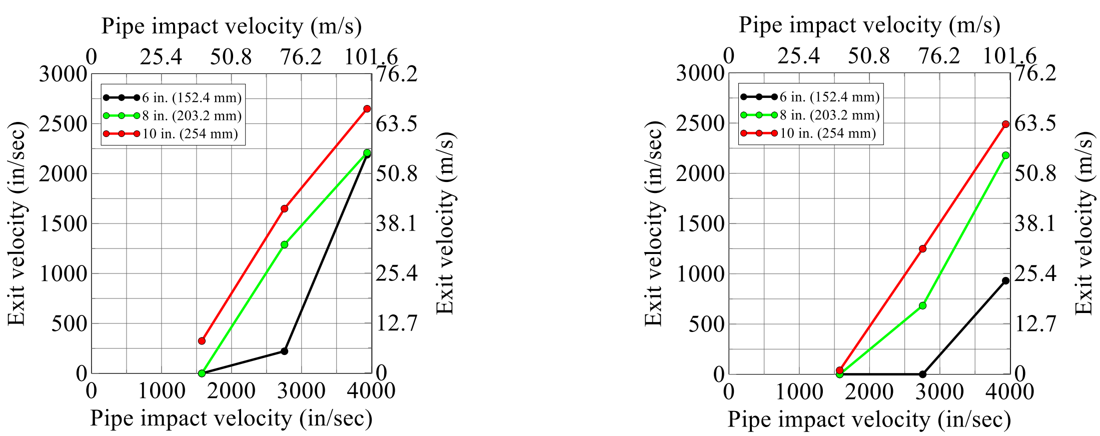


(a) f_t'=435 psi (3 MPa) (b) f_t'=725 psi (5 MPa)

Figure 5: Exit velocity of Schedule 40 pipe as a function of panel thickness, v=3937 in/sec (100 m/sec), f_c'=4351 psi (30 MPa)

Schedule 40 Pipe Impact Velocity and Concrete Compressive and Tensile Strength

The pipe exit velocity as a function of impact velocity is shown in Figure 6 for diameters of 6 in (152 mm), 8 in (203 mm), and 10 in (254 mm), and a concrete compressive strength of 4351 psi (30 MPa). The results are shown for tensile strengths of 435 psi (3 MPa) and 580 psi (4 MPa). The exit velocity of the pipe increases as the impact velocity increases: an expected result.

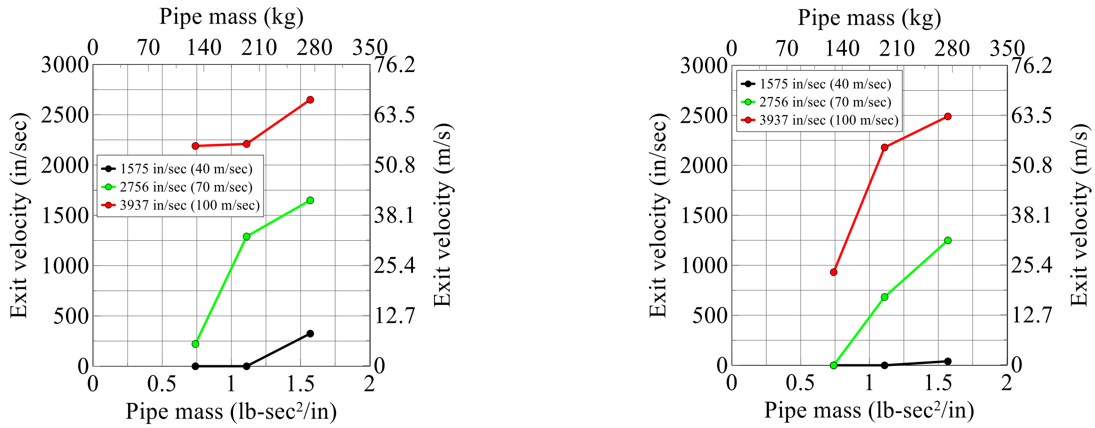


(a) f_t'=435 psi (3 MPa) (b) f_t'=580 psi (4 MPa)

Figure 6: Schedule 40 pipe exit velocity as a function of pipe impact velocity, Schedule 40 pipe, f_c'=4351 psi (30 MPa), 12-inch (305 mm) thick panel

Schedule 40 Pipe Diameter and Mass

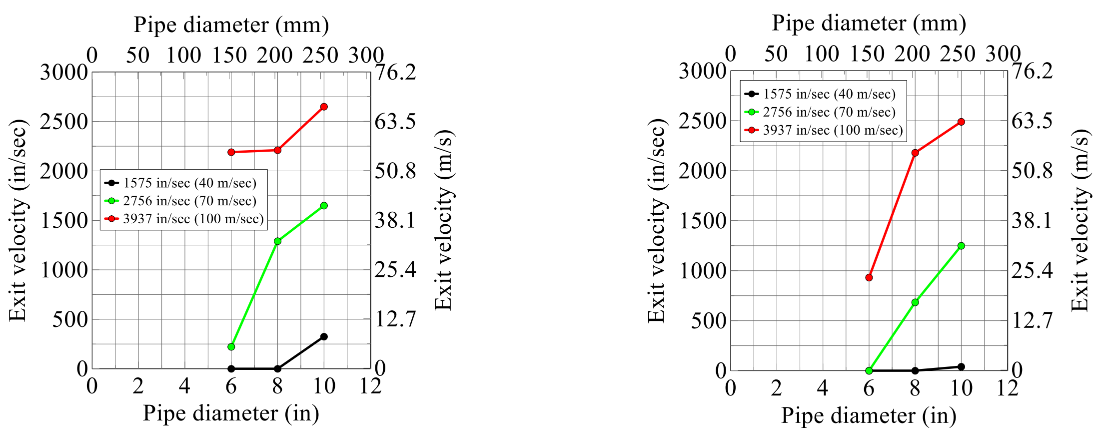
The exit velocity of the Schedule 40 pipe as a function of pipe mass is presented in Figure 7 for a concrete compressive strength of 4351 psi (30 MPa). The results are shown for concrete tensile strengths of 435 psi (3 MPa) and 580 psi (4 MPa). The pipe exit velocities increase as the mass of the pipe increases, which is an expected result considering that the mass of the 10 in (254 mm) diameter Schedule 40 pipe is twice that of the 6 in (152 mm) diameter pipe, resulting in nearly twice the kinetic energy being transferred to the panel during impact.



(a) f_t' =435 psi (3 MPa) (b) f_t' =580 psi (4 MPa)

Figure 7: Schedule 40 pipe exit velocity as a function of pipe mass, f_c'=4351 psi (30 MPa), 12-inch (305 mm) thick panel

The exit velocity of the pipe as a function of its diameter is presented in Figure 8 for a concrete compressive strength of 4351 psi (30 MPa). (The mass of the pipe increases with diameter.) Results are shown for tensile strengths of 435 psi (3 MPa) and 580 psi (4 MPa). The pipe exit velocity increases as the diameter of the pipe increases but the relative contributions of pipe diameter and mass to panel damage (i.e., perforation and scabbing) cannot be determined from these simulations alone. The effect of pipe diameter on impact resistance is investigated in the next section using a constant mass for all three pipes.



(a) f_t' =435 psi (3 MPa) (b) f_t' =580 psi (4 MPa)

Figure 8: Schedule 40 pipe exit velocity as a function of pipe diameter, f_c'=4351 psi (30 MPa), 12-inch (305 mm) thick panel

Schedule 40 Pipe Diameter with Constant Mass

The effect of pipe diameter on the impact resistance of a concrete panel was studied, with mass held constant. A 15 ft. (4572 mm) long Schedule 40 pipe with diameters of 6 in (152 mm), 8 in (203 mm), and 10 in (254 mm) were considered. The mass of each pipe was set that of the 10 in (254 mm) diameter Schedule 40 pipe (=1.95 lb-sec^2/in (276 kg)). The density of the material in the 6 in (152 mm) and 8 in (203 mm) diameter pipes was modified to achieve the target mass. Impact velocities of 1575 in/sec (40 m/s), 2756 in/sec (70 m/s), and 3937 in/sec (100 m/s) were considered. A 12 in (305 mm) thick panel with a concrete compressive and tensile strength of 4351 psi (30 MPa) and 725 psi (5 MPa), respectively, was used for the simulations. A description of the axisymmetric model used in the simulations is presented in Terranova et al. (2016). A concrete particle spacing of 0.08 in (2 mm) was used for all simulations, based on the mesh convergence studies presented in Terranova et al. (2017).

The exit velocities of the pipe as a function of diameter are presented in Figure 9. Perforation (exit velocity greater than zero) was observed for pipe impact velocities of 2756 in/sec (70 m/s) and 3937 in/sec (100 m/s). For these simulations, the exit velocity decreased as the diameter of the pipe increased. The predicted conical plug diameters increased as the diameter increased (see Terranova et al. (2017)), which engaged a larger shear failure plane (through the thickness of the panel) resulting in greater resistance to perforation and lower exit velocities. The reductions in exit velocity resulting from the diameter increase (see Figure 9) are significantly less than the increases in exit velocity caused by the increase in pipe mass (see Figure 7) indicating that the mass of the pipe has a much greater effect on the impact resistance of the panel than the pipe diameter.

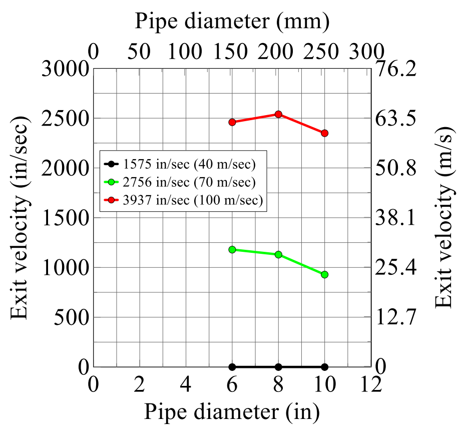


Figure 9: Schedule 40 pipe exit velocity as a function of pipe diameter with a constant mass

CONCLUSIONS

A parametric study was conducted using an axisymmetric SPH model to investigate the effects of panel thickness, Schedule 40 pipe size (mass and diameter), impact velocity, and concrete compressive and tensile strength on the resistance of reinforced concrete panels to impact loadings. Increases in panel thickness and concrete tensile strength significantly reduced the exit velocities of the pipe; concrete compressive strength had a small effect on the impact resistance of concrete panels. The increase in impact velocity and pipe mass resulted in greater exit velocities and more local damage to the panel (e.g., perforation and concrete scabbing); slight reductions in exit velocities were predicted as the pipe diameter increased for a constant mass indicating that the pipe mass has more effect on panel response than pipe diameter. The results of these studies could be used to draft technical guidance for the performance assessment of reinforced concrete panels impacted by wind-borne missiles.

REFERENCES

Borvik, T., Hopperstad, O. S., Dey, S., Pizzinato, E. V., Langseth, M., and Albertini, C. (2004). "Strength and ductility of Weldox 460 E steel at high strain rates, elevated temperatures and various stress triaxilities," *Engineering Fracture Mechanics,* 72, 1071-1087.

Comite Euro-international du Beton (CEB/FIP). (1990). "CEB-FIP model code 1990," Thomas Telford, London, England.

Dusenberry, D. ed. (2010). *Handbook for Blast Resistant Design of Buildings.* John Wiley & Sons. Hoboken, NJ.

Kennedy, R. P. (1975). "A review of procedures for the analysis and design of concrete structures to resist missile impact effects," *Nuclear Engineering and Design,* 37, 183-203.

Liu, G.R., and Liu, M.B. (2003). *Smoothed Particle Hydrodynamics: A Meshfree Particle Method*. World Scientifice, Singapore.

LSTC (2012). LS-*DYNA Keyword User's Manual V971*. Livermore, CA.

Stephenson, A. E. (1977). "Full-scale tornado-missile impact tests," *EPRI NP-440 Project 399*, Electric Power Research Institute, Sandia Laboratories, Albuquerque, NM.

Terranova, B., Whittaker, A.S., and Schwer, L. (2015). "Impact analysis of reinforced concrete panels for wind-borne missiles," *Transactions, 23rd Conference on Structural Mechanics in Reactor Technology*, Manchester, United Kingdom.

Terranova, B., Schwer, L., and Whittaker, A. S. (2016). "Wind-borne missile impact of reinforced concrete panels," *Proceedings, 24th International Conference on the Military Aspects of Blast and Shock*, Halifax, Nova Scotia, Canada.

Terranova, B., Whittaker, A. S., and Schwer, L. (2017). "Design of reinforced concrete panels for wind-borne missile impact," *MCEER report in preparation*, University at Buffalo, Buffalo, NY.

Terranova, B., Schwer, L., and Whittaker, A. S. (2018). "Resistance of reinforced concrete panels to impact by missiles generated by extreme winds," Paper submitted for review and possible publicaton, *Journal of Structural Engineering*.

Tu, D. and Murray, R. (1977). "Numerical simulation of tornado-borne missile impact," *UCRL-52223,* Lawrence Livermore Laboratory, Livermore, CA.

U.S. Nuclear Regulatory Commission (NRC). (2007). *Regulatory Guide 1.76: Design-basis tornado and tornado missiles for nuclear power plants*. Washington, DC.

U.S. Nuclear Regulatory Commission (NRC). (2011). *Regulatory Guide 1.221: Design-basis hurricane and hurricane missiles for nuclear power plants*. Washington, DC.

Vassallo, F. A. (1975). "Missile impact testing of reinforced concrete panels," *Calspan Report No. HC-5609-D-1*, Calspan Corporation, Buffalo, NY.