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PERFORMANCE OF SAFETY NETTING UNDER LOW VELOCITY IMPACT LOADING

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Abstract: In cases of overhead work in populated areas, industrial activities, construction, and mining, or other scenarios where the potential for projectiles to impact people, infrastructure, or other critical items, protection is required, sometimes in the form of a textile safety netting system. Temporary or permanently installed engineered safety netting may be used to reduce hazards from falling debris or flying projectiles. The nets must be designed to withstand the projectile impact force, be resistant to local failure due to stress concentrations, resist service loads due to environmental factors (snow, ice, wind, etc) and potentially absorb energy under impact scenarios. To ensure that the nets perform well under these loading scenarios, experimental validation is often required. This paper presents the performance of a series of safety nets of different configurations tested under low velocity impacts. A large bore single stage air driven launcher located at the University of New Brunswick's Ballistic and Mechanical Testing lab was used to propel standard clay bricks at impact velocities of up to 280km/h (77.7m/s) into the test specimen nets. The nets, comprised of single or multiple layers of material, were 3m square and supported in different configurations to a reaction frame. High speed video was used to monitor the projectile and net performance under impact. The overall performance of the different configuration of the nets are presented. Conclusions and recommendations related to net configuration and connection details are provided.

1 INTRODUCTION

Safety netting may be employed as a temporary or permanent method of preventing debris from impacting people or other sensitive items in dangerous environments. From a civil engineering perspective, these nets may be used in active construction zones in populated areas (Krishnamurthy 2013), mining applications, or as part of protective barriers between roadways and populated areas, among other applications. Debris retention netting is commonly used to restrain falling rock (Yang et al. 2017, Nicot et al. 2001), in sporting stadiums (Bohm et al. 2007), and in unique applications like car racing windows (Patalak et al. 2014). In this paper, nets are tested under impact that may be more easily characterized by falling construction debris, but the safe design principals are constant for all applications: protect life safety by eliminating impacts or reducing impact energy.

The risk to human life safety from impact is complicated by variables including projectile size, hardness, velocity, and where it strikes on the body. However, generally agreed upon critical energy levels are present for low velocity (subsonic) strikes of rigid projectiles. Valsamos et al. (2015) summarized the 80 Joule rule as simply the kinetic energy threshold where impacts present a high risk of death. More nuanced approaches, such as the Lewis formula, which is also summarized by Valsamos, incorporate more information but lead to similar conclusions. Figure 1 shows the velocity and mass combinations that would result in high probability of human death from both the Lewis formula and the 80 Joule rule. Overlayed on that figure is the mass and range of velocity used in this study. As can be seen, there are several combinations of mass and velocity employed in this study that would be above the 80J iso-damage line (and those of some of the Lewis curves as well).

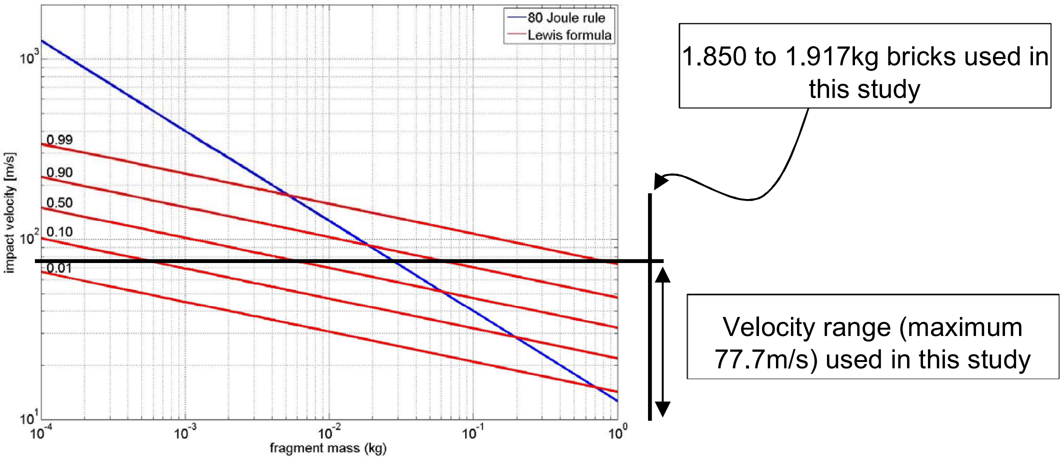


Figure 1: Human death risk thresholds to impact (adapted from Valsamos et al. 2015)

This program explores the capacity of different configurations of safety nets under low velocity impacts. The impactor in this study is a common clay brick, often used in residential and commercial construction for facades, infill walls, and load bearing walls. The nets are commercially available heavy duty and light duty safety nets made from nylon and PVC coated polyester fibre.

2 TESTING PROGRAM

2.1 Ballistics Test Lab

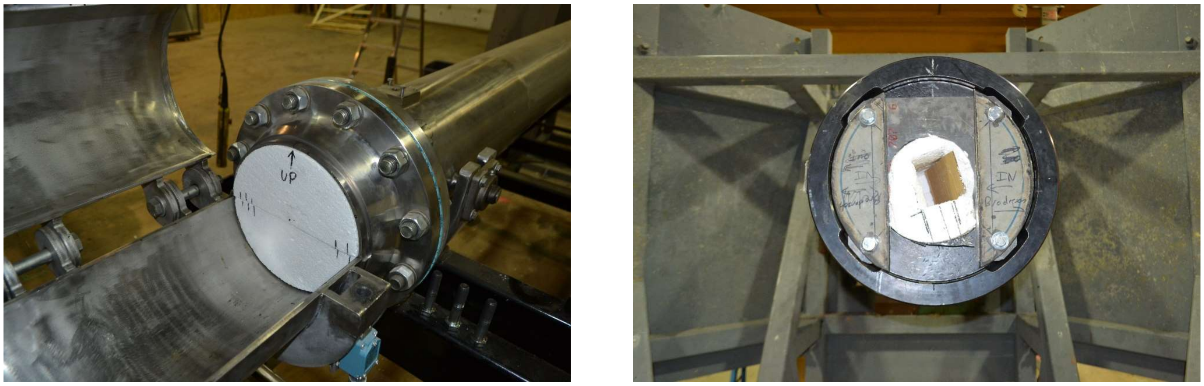
Testing for this project was conducted at the University of New Brunswick's Ballistics and Mechanical (BAM) Test Lab in Fredericton, New Brunswick. This lab is equipped with an array of ballistic launchers including multiple configurations of light gas guns capable of firing projectiles at hyper-velocities up to approximately 8000m/s and multiple configurations of subsonic, air-driven launchers. This project employed a large bore foreign object debris (FOD) gun shown in Figure 2 is capable of launching projectiles up to 250mm in cross-section dimension at velocities up to approximately 300m/s depending on mass.

Figure 2: Large bore FOD gun at UNB BAM Lab

This gun operates by charging a pressure reservoir with desired driver pressure using a computer-controlled interface. Once the desired pressure is achieved, an electronic trigger is switched, causing a fast opening butterfly valve to open and release the pressure in the reservoir. This pressure then acts upon the sabot housing the projectile in the breach of the barrel causing it to accelerate down the length of the barrel. Once the sabot reaches the end of the barrel, a stripper mechanism removes the sabot from the projectile allowing the projectile to continue towards the target and retaining the sabot in the barrel of the gun.

For the testing in this project, the sabot was formed by machining a 350mm long cylinder of expanded polystyrene to the barrel diameter (250mm). Once the cylinder was made, it was sawed in two equal pieces along the length and a cavity for the projectile was carved out of the foam on each side of the cut. Once the projectile was tightly fit in the cavity (Figure 3b), the two sides of the sabot were taped together (Figure 3a) such that the projectile was inset by 50mm from the end of the sabot foam (Figure 3c). The sabot used in this project is shown mounted in the breach in Figure 3d and the stripped sabot after a shot in Figure 3e. Sabots were consumable and needed to be replaced after each shot.

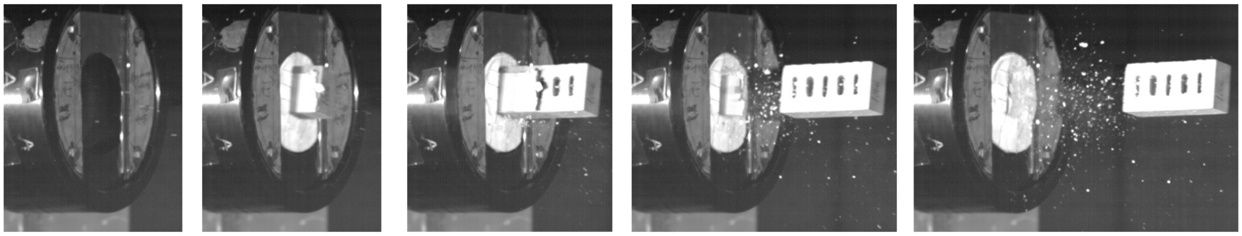
a) Empty sabot b) Brick projectile mounted in sabot cavity c) Projectile mounted in sabot



d) Loaded sabot mounted in breach e) Stripped sabot retained in barrel after shot

Figure 3: Sabot used in FOD gun

A view of the projectile exiting the barrel is shown in Figure 4 over a 20ms period. In this figure, it is evident that the projectile housed by the sabot reaches the end of the barrel where the sabot is stopped by the stripper plate and the projectile slips from the sabot and continues towards the target. Variations in friction and the precision of the sabot cavity to house the brick had slight implications on variability of velocity during testing. All reported velocities in this paper were those recorded during the test.



0ms 5ms 10ms 15ms 20ms

Figure 4: Brick projectile exiting FOD barrel during test

An array of high-speed cameras were used to monitor these tests as shown in Figure 5. The cameras included two Photron SA-X cameras that recorded the overall performance of the net from different angles and also were used for motion tracking of the projectile to record impact velocity and impact angle along with exit velocity or rebound velocity if applicable. The SA-X cameras recorded at 3000 frames per second at 1024 by 1024 pixel resolution. An additional high speed (AOS S Motion in Figure 5) camera recording at 1000 frames per second was used to monitor the projectile exit from the barrel to ensure proper firing of the gun was achieved. All cameras were set to record data on a continuous loop, saving data to an internal camera buffer. Once the gun was triggered, an electrical impulse was sent to the cameras and the data was saved for a period of approximately 7 seconds. That full video record was reduced to approximately 1 to 2 seconds of images that contained the impact and full response of the specimens in post processing.

Figure 5: High speed camera array

2.2 Test Specimens

For this program, a total of 12 tests were performed on a total of 8 different netting specimens. Some specimens were tested multiple times if no damage was detected on the first test. Of the 8 different specimens, there were at total of 4 different net materials. Some tests were conducted on single-layered materials, and some were conducted on combinations of materials layered together.

All nets were supplied by Barry Cordage Ltd. of Montreal, Canada. The nets were comprised of either knotless (raschel) nylon or PVC coated polyester netting with different cord diameters, mesh opening sizes and break-strengths. Netting types used in this project are classified as light or heavy duty, or as debris mesh and each serve different industrial applications. The properties of each type of net are provided in Table 1.

Table 1: Safety net properties (Barry Cordage Ltd. 2021)

Designation	Material	Cord diameter	Mesh Size (mm)	Mesh Strength	Type
FN700-2.5	Knotless Nylon	6.35mm	63.5x63.5	3114 N	Heavy Duty
FN700-1.5	Knotless Nylon	6.35mm	38.1x38.1	3114 N	Heavy Duty
FN100-0.5	Knotless Nylon	1.59mm	12.7x12.7	445 N	Light Duty
BTMLC1	PVC-coated polyester fibre	1000 denier	6.35x6.35	32.9 N/mm (warp) 20.0 N/mm (fill)	Debris Mesh

Each of the nets used in this project are shown at approximate scale in Figure 6. The two smaller types of nets used in this project, the nylon FN100-0.5 and PVC-coated polyester fibre BTMLC1, are shown in combination with one of the higher capacity nets (FN700-1.5 or FN700-2.5) as they were tested in a multi-layer configuration.

a) FN700-1.5 b) FN700-2.5 c) FN100-0.5 + FN700-2.5

d) BTMLC1 + FN700-1.5 e) BTMLC1 + FN700-2.5 f) Approximate scale

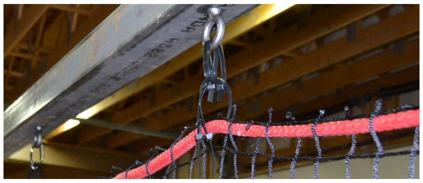
Figure 6: Different safety nets tested in project

The nets were connected to a structural steel frame which was then bolted to the laboratory floor. The structural steel frame, shown in Figure 7, was made from HSS102x102x4.8 steel sections welded together. The frame was bult to accommodate the 3.048m square nets. Gusset plates were added in the corners to accommodate steel shackles used to connect the net to the frame. Additional interior supports at 1/3 span points around the perimeter were included using eyebolts and either cable ties or rigid steel links to connect to the perimeter cable of the net.

The interior connections for all but one of the nets were comprised of doubled up cable ties with specified break strength of 445N each or an assumed 890N in pairs. These ties were used to remove the slack in the net while allowing for a progressive failure mode with the idea that the ties would break under large impact forces prior to the net allowing the projectile to pass through. The large deformation in those extreme events was determined to be acceptable over failure to prevent pass through of the projectile. One net was connected at interior points with a rigid steel link system and tested to allow for direct comparison of behaviour with the cable tied nets. Figure 7 shows the interior and corner connections used in this test program.

a) Testing frame with net installed

b) Shackled corner connection



c) Cable tied interior connection

d) Steel link interior connection

Figure 7: Steel reaction frame and net-to-frame connections

Table 2 provides information on the nets tested in this project including the test number, the configuration of nets, the impact mass of the brick projectile and the impact velocity. The impact energy is also computed as the kinetic energy of the brick at the time of impact. Additional information on rebound and exit velocity and energy of the projectile is provided in Table 2, these are discussed later in this paper.

Table 2 shows that 4 of the 12 specimens tested had double net configurations (tests 8, 9, 10, and 11). In each of these tests, the lighter net (FN100-0.5 or BTMCL1) was placed on the impact side of the configuration such that the projectile impacted the smaller net first then the higher capacity backing net (FN700-1.5 or FN700-2.5). These nets were installed without any gap between the pairs.

Table 2: Net configurations and impact performance

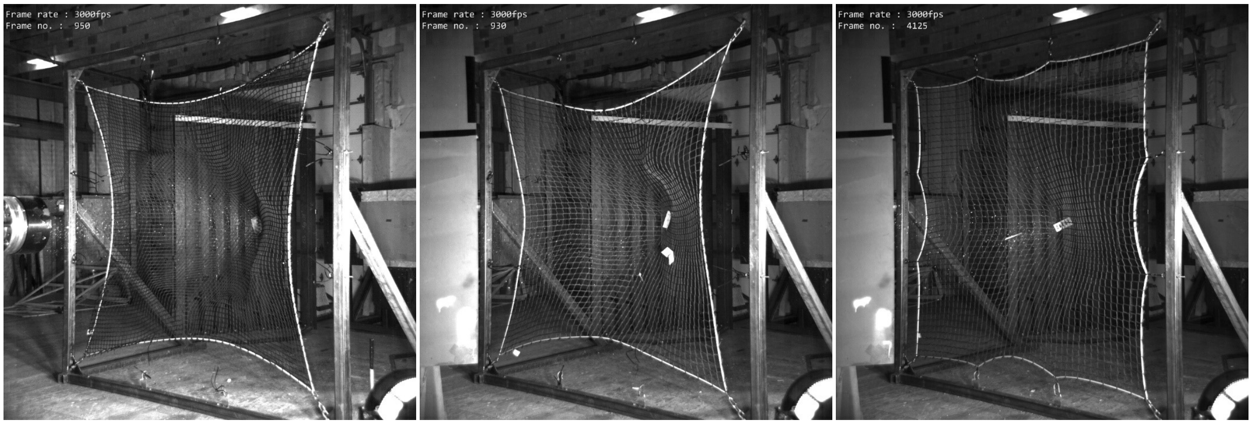
Test	Configuration	Impact mass (g)	Velocity (m/s)			Energy (J)		
			Impact	Exit	Rebound	Impact	Exit	Rebound
1	FN700-1.5	1853	15.7	-	Low	228	-	-
2	FN700-1.5	1869	14.1	-	Low	186	-	-
3	FN700-1.5	1870	41.7	-	11.5	1626	-	124
4	FN700-2.5	1917	28.2	-	7.3	762	-	51
5	FN700-2.5	1866	25.5	-	Low	607	-	-
6	FN700-2.5	1867	40.1	-	12.5	1501	-	146
7	FN700-1.5	1873	36.6	-	12.7	1254	-	151
8	FN100-0.5 + FN700-2.5	1850	27.4	-	Low	694	-	-
9	FN100-0.5 + FN700-2.5	1875	77.7	72.4	-	5660	4914	-
10	BTMLC1 + FN700-1.5	1870	37.1	-	-	1287	-	-
11	BTMLC1 + FN700-1.5	1867	40.7	-	-	1546	-	-
12	FN700-2.5	1872	39.5	19.1	-	1460	341	-

3 EXPERIMENTAL RESULTS

3.1 Single Layer Net Tests

This testing was conducted to try to determine the approximate capacities of the nets for the given brick impactor. Tests 1 to 7 explored the performance of the high capacity nets (FN700-1.5 and FN700-2.5) under various impact conditions. In general, these nets saw no failure up to 41.7m/s impact velocity and a corresponding impact energy of 1626J. For the low velocity tests (such as Test 1 and Test 2) typically none or very few of the interior cable tie supports for the nets failed whereas for the high velocity tests (Tests 3 and 6) all of the interior cable ties failed. Views of these nets at maximum displacement condition are shown in Figure 8a and b where it is evident that all of the ties did break allowing for more deformation in the net along with the energy absorption and reduction in stiffness that allowed the nets to restrain the projectile completely. Figure 9a and b show the response of the high velocity tests on the FN700-1.5 (Test 3) and FN700-2.5 (Test 6) nets that were supported using cable ties over time.

Test 12 tested the same type of net as Test 6, FN700-2.5, under a similar velocity. However, Test 12 employed rigid steel links supporting the interior of the net rather than the cable ties. This net failed early on in response, approximately 33ms after the first impact, as the projectile broke the cords in the net and passed through with a significant exit velocity. In this case, the exit velocity was 19.1m/s with a corresponding 341J of kinetic energy, well above the critical injury threshold of 80J. The side view of Test 12 is shown at various times in comparison with other similar nets in Figure 9c and the net condition at the time of failure is shown in Figure 8c.

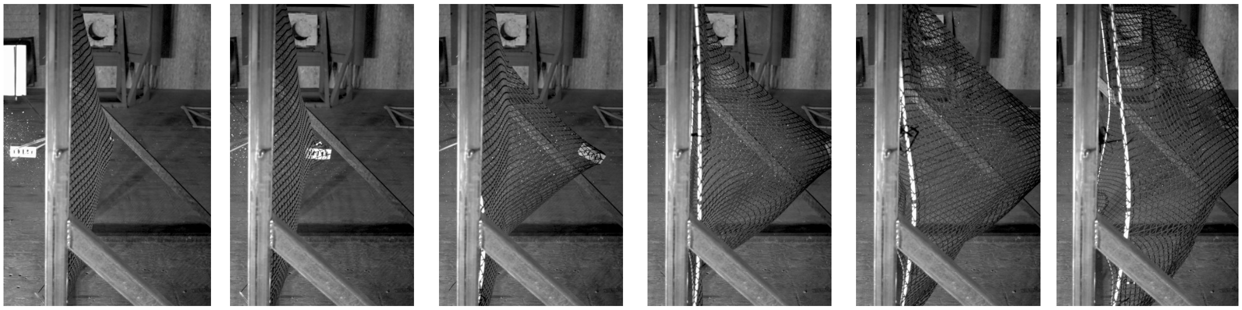


a) Test 3 FN700-1.5 with cable tie interior support at maximum deformation

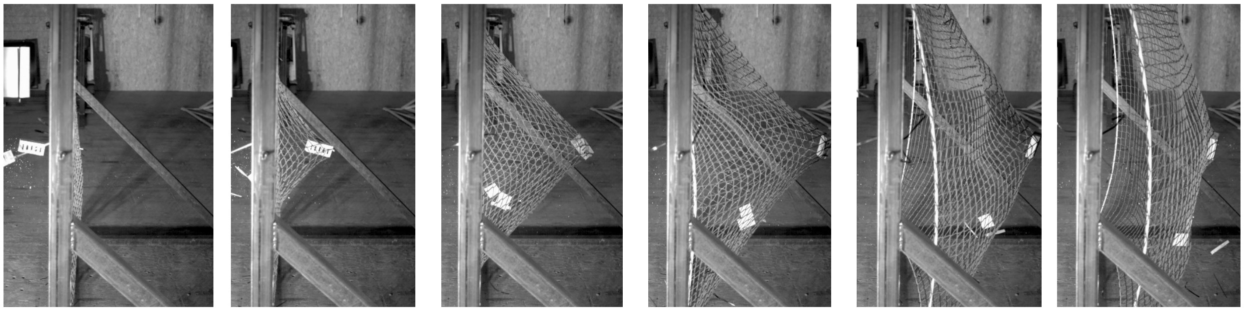
b) Test 6 FN700-2.5 with cable tie interior supports at maximum deformation

c) Test 12 FN700-2.5 with rigid link steel interior supports at failure

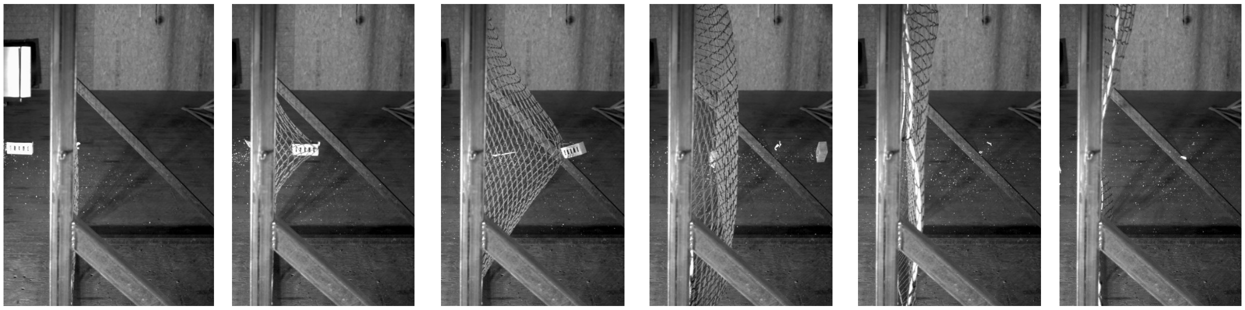
Figure 8: Performance differences based on interior support conditions



a) Test 3 FN700-1.5 at 41.7m/s (cable tie interior supports)



b) Test 6 FN700-2.5 at 40.1m/s (cable tie interior supports)



c) Test 12 FN700-2.5 at 39.5m/s (rigid steel link interior supports)

Figure 9: Response of select nets under high energy impact over time

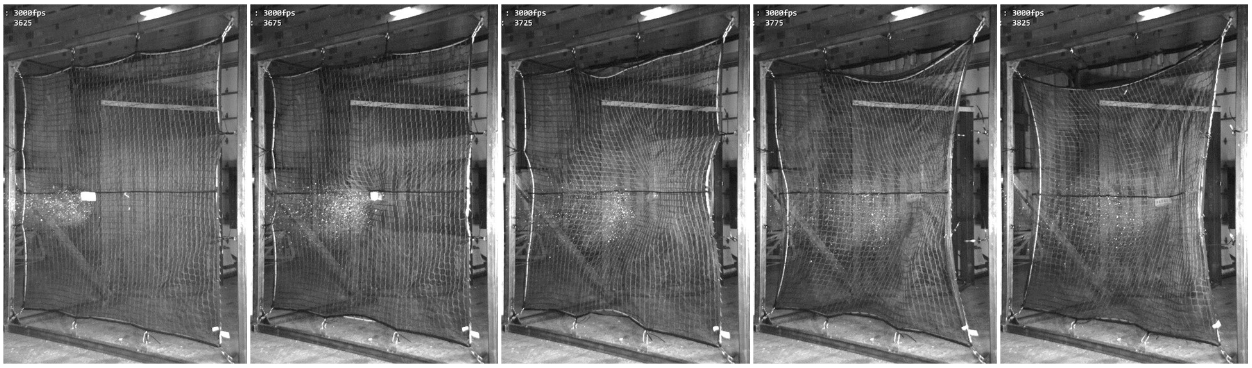
3.2 Rebound Hazard and Multi-Layer Configurations

Even if the net does restrain the projectile, one potential hazard is the projectile rebounding backwards at a high enough velocity to become dangerous. Depending on the end use case of safety netting, this may not be a significant design consideration, but if people or items of concern are present on the impacted side of the net, rebound may become a concern. In this testing program, several of the nets had significantly high rebound velocities such that the rebound energy was above the potential critical injury threshold of 80J. Figure 10 shows the rebound of the projectile from Test 3. In this test, the rebound energy was 124J, enough to be considered critical if impacting humans, with the velocity of 11.5m/s. In Figure 10d the projectile can be seen shattering on the barrel of the launcher located approximately 2m away from the net.

a) Maximum deformation b) 150ms after maximum c) 217ms after maximum d) 283ms after maximum

Figure 10: Test 3 FN700-1.5 with an impact velocity of 41.7m/s and a rebound velocity of 11.5m/s

Test on the double layer nets show that prevention of rebound may be achieved by employing the incremental failure of the net pairs such that the projectile may become trapped between layers of the net. Careful design could result in systems that are elastic up to the point where rebound energy becomes critical. At that point, the failure of the first net could be used to entangle the projectile and prevent rebound completely. This was observed in Tests 8, 10, and 11 of this program, with Figure 11 showing the retention of the projectile in Test 11. Test 9, however, shows that double layer configurations do have limitations as the projectile impact velocity and energy were high enough to break through both layers of the net with an exit velocity of 72.4m/s, only a slight reduction from the 77.7m/s impact velocity, and an exit energy well above critical levels at 4914J.



0ms 16.7ms 33.3ms 50ms 66.7ms

Figure 11: Brick being retained by combination BTMLC1 and FN700-1.5 net in Test 11 at 40.7m/s

4 Conclusions

Several different types of safety netting were tested under low velocity impacts representative of falling debris or industrial accidents. Different velocities, boundary conditions, and layup configurations of nets were used in this testing.

The following conclusions may be drawn from the observations made during this experimental program:

- Correctly designed nets may be effective in restraining projectiles.
- The nets tested in this study that were restrained with sacrificial cable ties were able to restrain the brick projectiles up to a velocity of 41.7m/s without projectile pass through.
- Rebound of projectiles may be of significant energy to present a hazard. This rebound hazard was observed to be present in moderate velocity tests that did not cause significant damage to the nets.

- High enough impact energy and velocity will cause rapid failure of the nets and result in pass through of the projectile with little reduction in velocity and energy. This was observed in conditions of high impact velocity (Test 9 at 77.7 m/s) and moderate impact velocity with rigid interior supports (Test 12 at 39.5 m/s)
- Light duty netting may be employed effectively in concert with heavy duty net to restrain projectiles from both passing through the net and from rebounding from the net.
- The use of sacrificial interior connections, cable ties in this case, allowed the nets to be securely installed for service conditions and to absorb impact energy during impact events. These sacrificial elements clearly demonstrated their contribution to enhanced impact performance over rigid connections by direct comparison of performance between Test 6 and Test 12.

Further validation of safety nets under different impact conditions including impact velocity, impactor configuration, impact angle, and overall net geometry and materials should be done to fully generalize these conclusions.

Acknowledgements

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References

Bohm, H., Schwiewagner, C., and Senner, V. 2007. Simulation of puck flight to determine spectator safety for various ice hockey board heights, *Sports Engineering* **10**: 75-86.

“Collections,” Barry Cordage Ltd., Accessed March 4, 2021. https://www.barry.ca/collections/

Debek, C., Wasileqicz, A., and Czyz., T. 2017. Investigation and FEM analysis of mineshaft rope safety platforms in underground mining, *The Journal of the Southern African Institute of Mining and Metallurgy*, **117**: 373-380.

Krishnamurthy, N. 2013. Safety during Steel Erection, *The Pacific Structural Steel Conference* PSSC, Singapore.

Nicot, F., Cambou, B., and Mazzoleni, G. 2001. Design of Rockfall Restraining Nets from a Discrete Element Modelling, *Rock Mechanics and Rock Engineering*, **34**(2): 99-118.

Patalak, J., Gideon, T., and Krueger, D. 2014. Design, Development and Testing of an Improved Stock Car Driver’s Window Net Mounting System, *SAE International Journal of Transportation Safety*, **2**(1): 165-181.

Valsamos, G., Casadei, F., Larcher, M., and Solomos, G. 2015. Implementation of Flying Debris Fatal Risk Calcualtion in EUROPLEXUS, *Institute for the Protection and Security of the Citizen*. Joint Research Centre of the European Commission, Luxembourg.

Yang, J., Chen, Y., Xhang, Z., and Luo, R. 2018. Falling Weight Impact Test of a New-Type Flexible Rock-Shed, *Engineering Review*, **38**(20): 242-252