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June 25, 2009

Sureguard Security Products
18 Wilhelm St.
Kitchener, ON N2H 5R8

Attention: **Robert Vogt**
General Manager
rvogt@sureguard.ca

Reference: **Report – Flexural Testing of Bollards**

Dear Mr. Vogt:

Three types of bollards proposed by Sureguard Security Systems (Sureguard) were tested in the Structures Laboratory at the University of Waterloo on April 16, 17 and 20, 2009. The following reports the testing procedure and detailed test results. A brief analysis of the findings is also included.

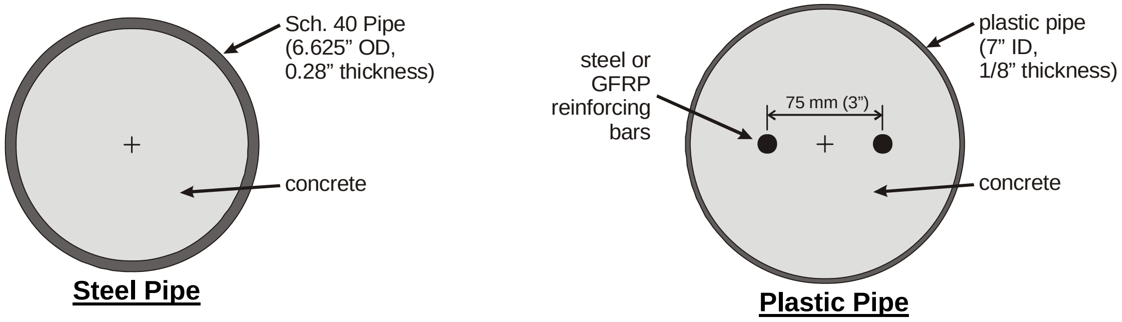
Bollard Specimens

The bollard specimens were constructed at the University of Waterloo using materials supplied by Sureguard and ready-mixed concrete. Three types of bollards were constructed as detailed in Table 1. Each type was constructed in triplicate for a total of nine (9) bollard specimens.

Table 1 – Bollard Specimen Details

Designation	Pipe	Reinforcement
Steel	Steel: 6.625” O.D., Schedule 40	None
Plastic-S	Plastic: 7” I.D., 1/8” thick	Two 10M bars (hairpin)
Plastic-G	Plastic: 7” I.D., 1/8” thick	Two 0.5” dia. GFRP bars

The 10M reinforcing bars were standard deformed reinforcing bars with a minimum yield strength of 400 MPa. The GFRP bars were V-Rod glass fibre-reinforced polymer (GFRP) bars provided by Trancells Construction Technologies. The 0.5 in. (12.7 mm) GFRP bars, manufactured by Pultrall, Inc., have an ultimate tensile strength of 786 MPa, a guaranteed design tensile strength of 708 MPa and a tensile modulus of elasticity of 46.3 GPa (published data). The reinforcing bars (steel and GFRP) were centred in the pipe specimens with a spacing of 75 mm c/c, as shown in Figure 1. The bollard specimens were tested in flexure with the cross-section oriented as shown in the figure.



Steel Pipe

Plastic Pipe

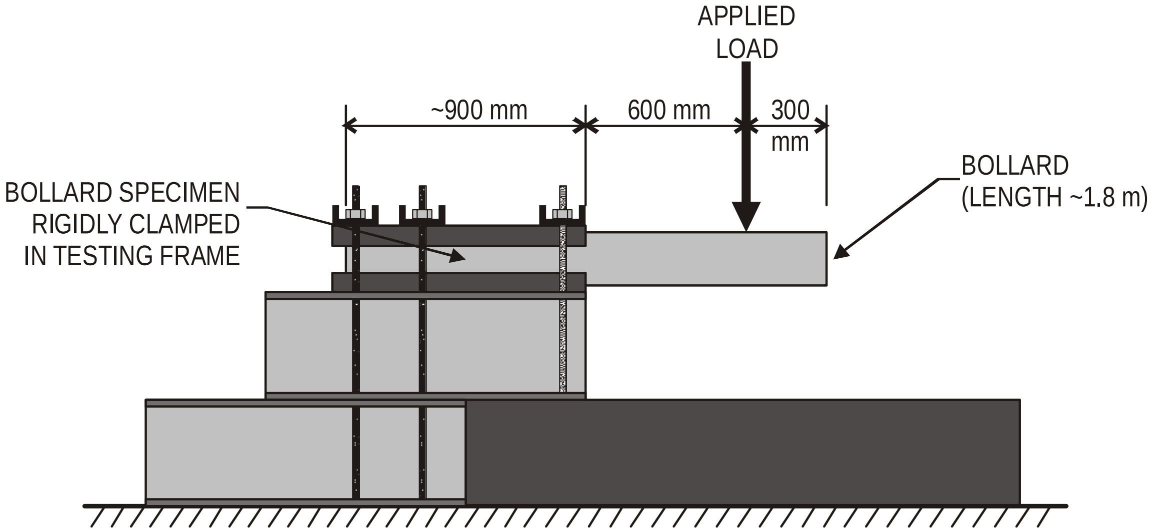
Figure 1 – Bollard Specimen Cross-sections

The bollards were filled with ready-mixed concrete in three lifts. Each lift was vibrated before proceeding with the subsequent lift. The concrete had a water/binder ratio of 0.52 and a slump of 100 mm. The average cylinder compressive strength at the time of bollard flexural testing was 27.6 MPa. No special curing measures were employed for the bollards. The cylinders were removed from the moulds after 48 hours and air-cured until the time of testing.

Testing Procedure

The bollards were loaded to failure in bending (flexure) in a testing frame (500 kN capacity) in the Structures Laboratory at the University of Waterloo. The bollard specimen was mounted in the testing frame as shown in Figure 2. A free-length of 900 mm was used to simulate the bollard length above ground. The loading was applied at a distance of 300 mm from the bollard tip, or 600 mm from the support, to simulate a typical vehicle bumper height.

The test fixtures rigidly clamped the bollard to the test frame and allowed the strength of the bollard in bending to be determined. Note that the testing configuration does not represent the actual conditions of installation or use for the bollards. However, the test configuration provided a relative strength comparison between the standard steel bollard and the plastic bollard. The portion of the bollards that would normally be embedded in the ground was clamped in the test frame using steel channel sections. Wooden wedge strips were used to provide relatively uniform bearing of the circular bollards on the channels (see Figure 3). A steel v-block was used to transfer the applied load to the bollards, as shown in Figure 3. The bearing surface of the v-block was rounded to avoid a sharp surface in contact with the bollard.



Schematic

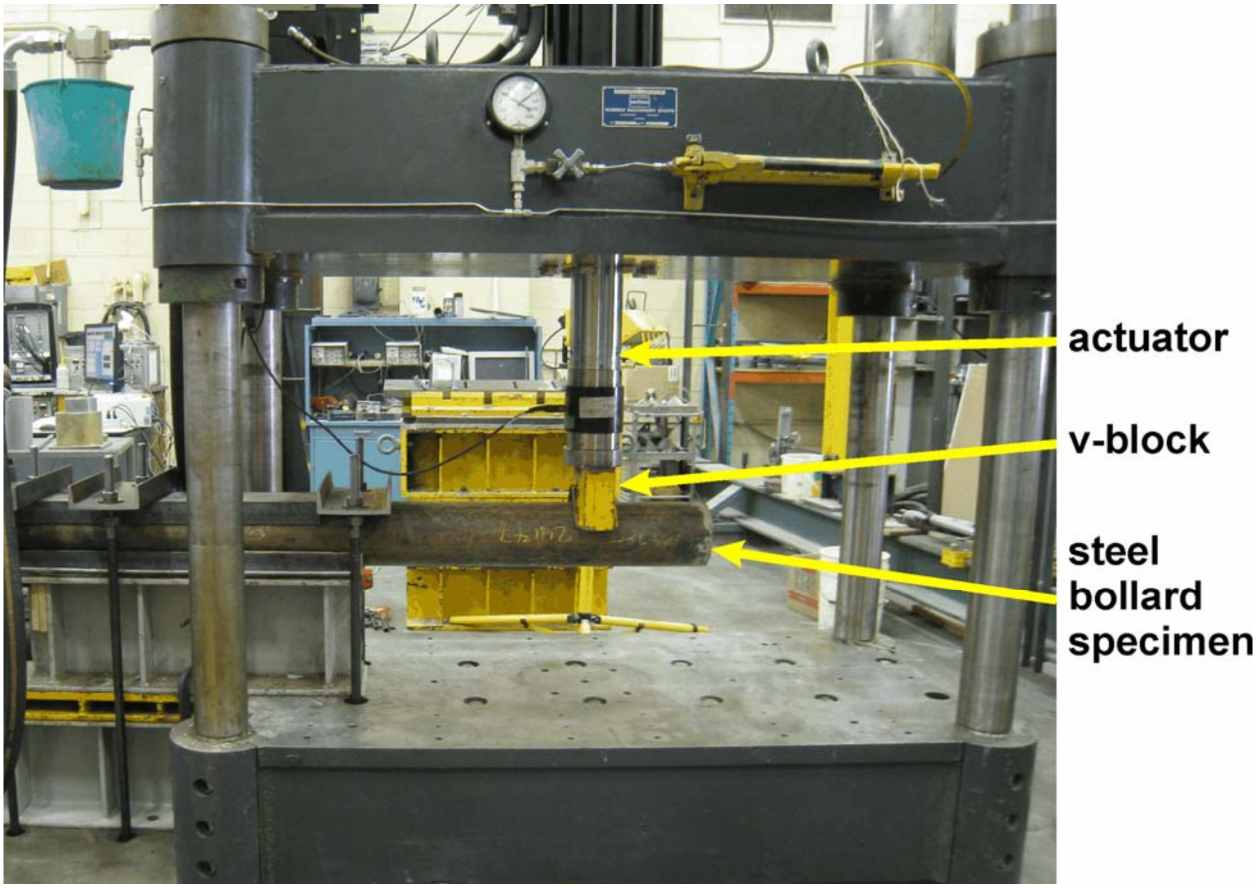


Figure 2 – Bollard Flexural Testing Configuration

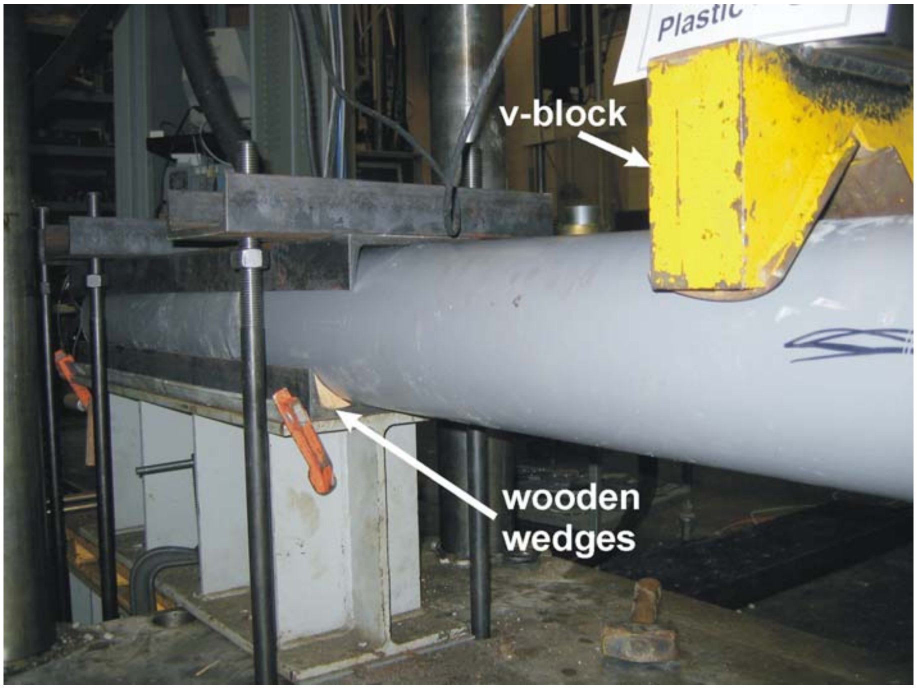


Figure 3 – Bollard Testing Configuration – Support and Loading Details

Loading was applied using a servo-controlled hydraulic actuator operating in stroke control at a constant stroke rate. Tests were continued until failure of the bollard occurred (i.e., significant reduction in load-carrying capacity), or until a stroke (displacement) of 200 mm was reached. Two stroke rates were considered: 10 mm per minute (slow, static load test), and 50 mm per second (rapid). The slow loading rate of 10 mm per minute is intended to capture the full, static flexural behaviour of the bollards. The more rapid rate of 50 mm per second is intended to assess load rate dependent strength and ductility effects; however, it does not simulate a vehicle impact. The applied load and actuator stroke were continuously recorded by a computer data acquisition system during the tests.

<u>Test Results – Failure Modes</u>

All nine (9) bollard specimens failed at the "base" of the bollard (adjacent to the fixed length). The failure conditions for the steel and plastic bollards are shown in Figure 4 and Figure 5, respectively.

For the steel bollards, a significant reduction in load carrying capacity coincided with rupturing of the steel pipe on the tension side (top) of the bollard. Prior to failure, distortion and "bulging" of the compression side was noted, suggesting damage of the confined concrete core had occurred. The typical condition of the steel bollard at failure is shown in Figure 4. The steel bollard specimen tested at a higher load rate (Steel-3) displayed a very large crack/rupture, indicating that the ductility of the steel is strain-rate dependent (see Figure 4).

Failure Condition – Slow Load Rate

Failure Condition – Faster Load Rate

Distortion and Bulging of Pipe – Slow Load Rate

Pipe Rupture and Bulging – Faster Load Rate

Pipe Rupture on Tension Surface – Slow Load Rate

Pipe Rupture on Tension Surface – Faster Load Rate

Figure 4 – Typical Steel Bollard Condition at Failure

Failure Condition – Slow Load Rate

Failure Condition – Faster Load Rate

Distortion and Bulging of Pipe – Slow Load Rate

Pipe Rupture and Bulging – Faster Load Rate

Pipe Yielding on Tension Surface – Slow Load Rate

Pipe Rupture on Tension Surface – Faster Load Rate

Figure 5 – Typical Plastic Bollard Condition at Failure

The failure condition of the plastic pipe bollards was independent of the internal reinforcement type. A reduction in load carrying capacity coincided with distortion and bulging of the pipe on the compression side. For specimens tested at the lower load rate (Plastic-S1, Plastic-S2, Plastic-G1 and Plastic-G2), the plastic pipe did not rupture. However, "yield lines" were clearly visible on the tension surface of the plastic pipe. The typical condition of the plastic bollards at failure is shown in Figure 5. The two specimens tested at the higher load rate (Plastic-S3 and Plastic-G3) developed a large rupture of the plastic pipe on the tension side at the critical section, indicating that the ductility of the plastic is strain-rate dependent. In both cases, a large concrete crack coincided with the rupture in the pipe. The internal reinforcement, visible through the crack, was not ruptured at failure (see Figure 5).

Test Results – Load and Displacement Data

The measured load-displacement behaviour for all bollards is shown in Figure 6. The same data are re-plotted for the steel and plastic pipe specimens in Figure 7 and Figure 8, respectively. The load data are the measured load (force) applied by the hydraulic actuator at a distance of 600 mm from the fixed length of the bollard (see Figure 2). The displacement data are the measured actuator stroke, which also corresponds to the lateral displacement of the bollard at a distance of 600 mm from the fixed length of the bollard base. Since the displacement values are based on the actuator stroke, they include a small displacement component due to deformation of the test frame and fixtures. However, this deformation component is very small in comparison to the deformation of the test specimen, and can be neglected for the purposes of this discussion.

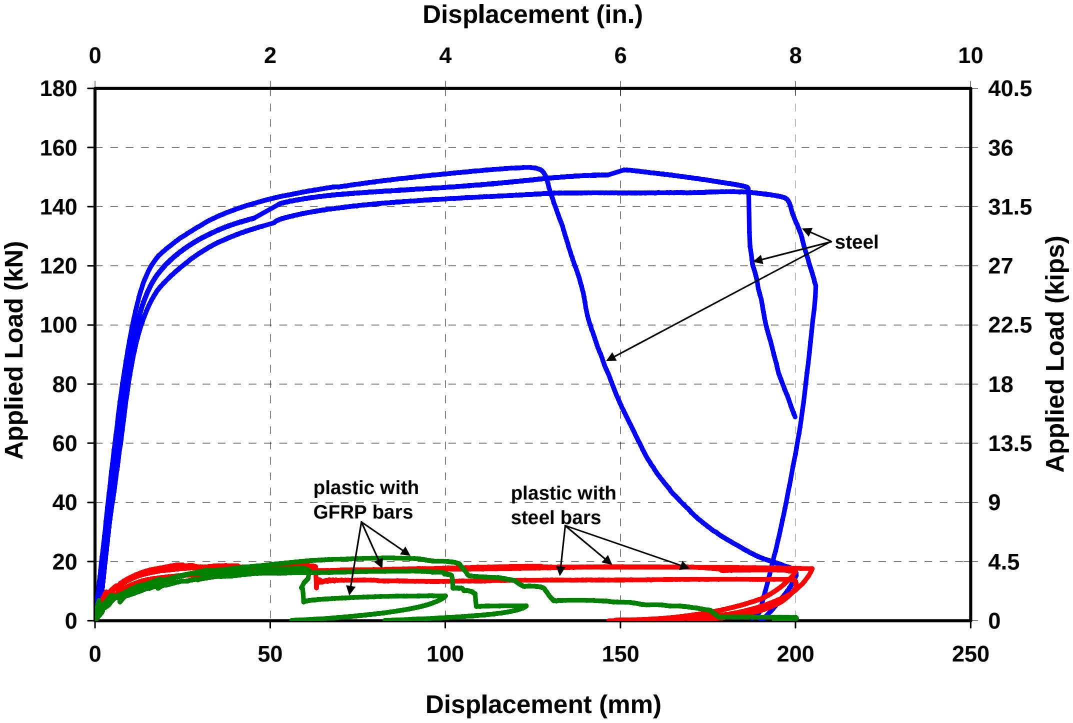


Figure 6 – Load-Displacement Data: All Specimens

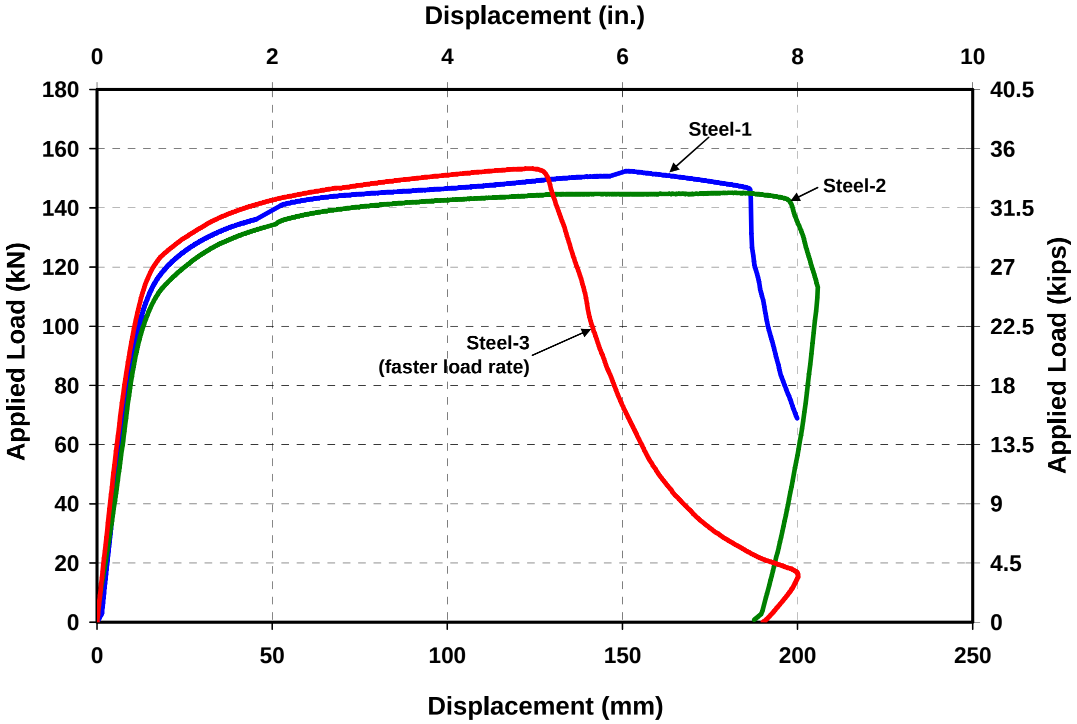


Figure 7 – Load-Displacement Data: Steel Bollards

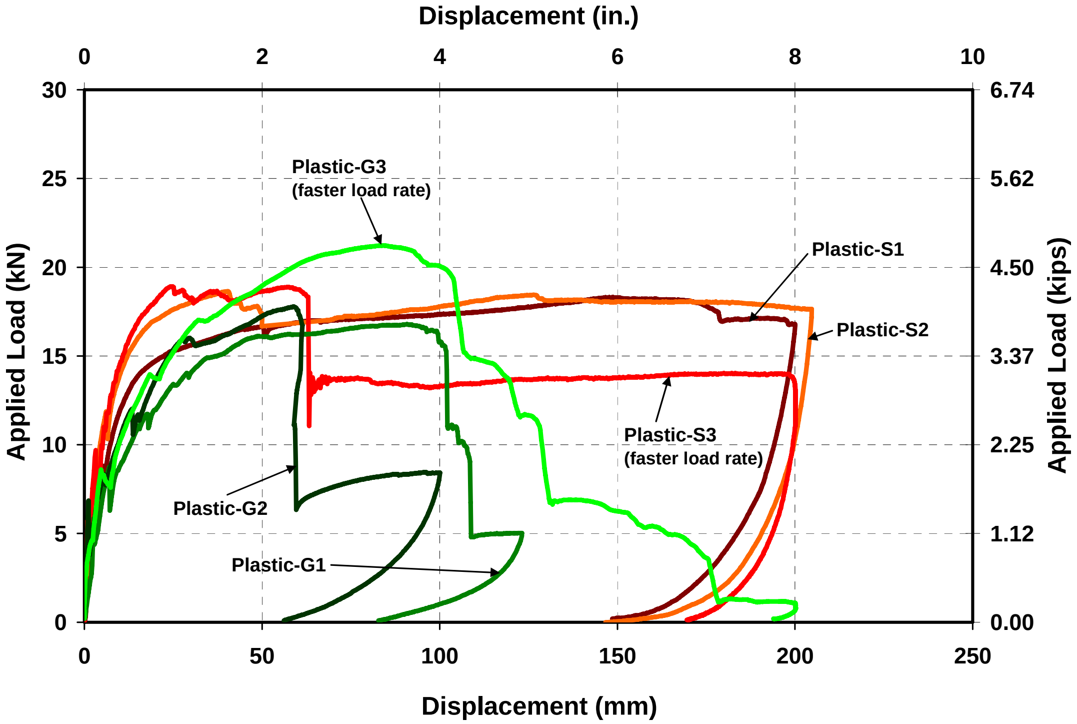


Figure 8 – Load-Displacement Data: Plastic Bollards

The test results are summarized in Table 2 in terms of maximum load, displacement corresponding to the maximum load, maximum displacement at failure (minimum 15% reduction in load) and displacement recovery after unloading. The displacement recovery is the difference between the maximum displacement recorded at the end of the test (with load still present) and the displacement after the load was completely removed. Data are presented and averaged for the specimens tested under the slow (static) load rate, while data for the specimens tested under the faster load rate are listed separately. As mentioned previously, all displacement values are based on the actuator stroke, and thus include a small, but negligible, displacement component due to deformation of the test frame and fixtures.

Table 2 – Bollard Flexural Strength Testing Results

Bollard Specimen	Maximum Load		Displacement at Maximum Load		Maximum Displ. At Failure**		Displacment Recovery***	
	(kN)	(lbs)	(mm)	(in.)	(mm)	(in.)	(mm)	(in.)
Steel-1	152.4	34,264	151.6	5.97	198.3	7.81	--	--
Steel-2	145.1	32,630	180.3	7.10	186.5	7.34	18.2	0.72
Avg.	**148.8**	**33,447**	**166.0**	**6.53**	**192.4**	**7.57**	**18.2**	**0.72**
Plastic-S1	18.3	4,117	148.7	5.85	200.1	7.88	51.5	2.03
Plastic-S2	18.6	4,191	40.5	1.59	204.7	8.06	58.1	2.29
Avg.	**18.5**	**4,154**	**94.6**	**3.72**	**202.4**	**7.97**	**54.8**	**2.16**
Plastic-G1	16.8	3,775	90.8	3.58	123.2	4.85	40.3	1.58
Plastic-G2	17.8	3,996	58.7	2.31	60.9	2.40	43.9	1.73
Avg.	**17.3**	**3,886**	**74.7**	**2.94**	**92.0**	**3.62**	**42.1**	**1.66**
Bollards Tested at Higher Load Rate*								
Steel-3	153.3	34,455	123.2	4.85	127.6	5.02	9.7	0.38
Plastic-S3	18.9	4,251	24.9	0.98	64.2	2.53	30.4	1.20
Plastic-G3	21.2	4,771	84.1	3.31	105.0	4.13	6.1	0.24

***** *Up to an imposed displacement of 200 mm*
****** *Failure indicated by min. 15% drop in strength*
******* *Bollard displacement recovered upon unloading at end of test*

Discussion of Results

Strength

The average static strength of the plastic bollards appears to be slightly higher (7%) for the steel-reinforced specimens in comparison to the GFRP-reinforced specimens: 18.5 kN versus 17.3 kN maximum load. The third specimen in each group (Plastic-S3 and Plastic-G3) was tested at a higher load (stroke) rate of 50 mm per second. The effect of the higher load rate on the bollard strength was minimal for the steel-reinforced specimens. However, it produced a 22% increase in strength for the GFRP-reinforced specimens. As a result, these limited data suggest that the GFRP-reinforced bollards may have a higher strength than the steel-reinforced bollards under high load rates. Further investigation is required to confirm this.

The strength of the steel pipe bollards was significantly higher than that of the reinforced plastic pipe bollards; the average static strength of the steel bollards was 148.8 kN, or 8.3 times higher than the average static strength for all of the plastic bollards. The higher load rate for specimen Steel-3 had a minimal effect on the strength of the steel bollard specimen.

The higher strength of the steel bollard is provided by the significantly larger area of steel in comparison to the steel and GFRP reinforcement of the plastic bollards. The larger steel area of the steel pipe provides a much larger moment of inertia in comparison to the plastic bollards, providing increased strength and stiffness.

Displacement Capacity and Recovery

The displacement capacity of the three bollard types was significantly different. The steel bollards tested under static loading maintained their load-carrying capacity up to an average displacement of 193 mm (~8 in.). However, the specimen tested under the higher load rate (Steel-3) reached a displacement of 128 mm (~5 in.) before failure occurred, indicating that the displacement capacity is strain rate sensitive.

The plastic bollards with steel reinforcement also sustained their load-carrying capacity at large displacements when tested under static loading (both reached displacements of 200 mm, although some reduction in load was recorded). The specimen tested under higher load rate failed (i.e., experienced a large reduction in load-carrying capacity) at a displacement of 64 mm (~2.5 in.). This coincided with rupturing of the plastic pipe (see Figure 5). However, it was able to further sustain a reduced load of approximately 13.5 kN up to a displacement of 200 mm (~8 in.), as shown in Figure 8. These data indicate that the displacement capacity of the steel reinforced plastic pipe specimens is also strain rate sensitive, most likely due to the strain-rate sensitivity of the plastic pipe itself.

The plastic bollards with GFRP reinforcement had the lowest displacement capacity, all failing at displacements of approximately 100 mm (4 in.) or less. The displacement capacity was largest for the specimen tested at the higher load rate (Plastic-G3). This trend is opposite to that observed for the other bollard types.

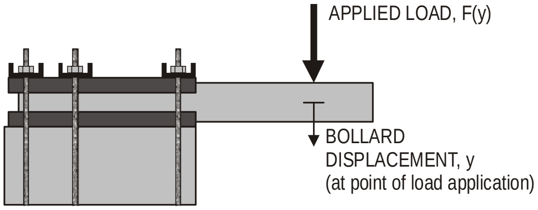
The displacement recovered upon unloading was pronounced for the plastic bollards, as visible in Figure 6 and reported in Table 2. The data show that the plastic bollards were able to recover approximately 40 to 50 mm (up to 2 in.) upon unloading, even after considerable inelastic deformation and damage had occurred in the form of concrete cracking and plastic pipe yielding or rupture. In contrast, the displacement recovery for the steel bollard was less than 20 mm (~3/4 in.). This difference in behaviour is attributed to the fact that the steel pipe ruptured in tension at failure, creating permanent damage/displacement that could not be recovered. In the plastic pipe bollards, the internal steel or GFRP reinforcement was still intact at failure, and thus was able to partially recover the displacement through elastic strain recovery upon unloading.

Energy Dissipation Through Inelastic Deformation

All of the bollard types displayed substantial damage or inelastic behaviour when loaded to failure. The ability of the bollard to absorb extreme loading (i.e., loading causing failure) can be described in a number of ways, including the capacity for energy dissipation through inelastic behaviour. The amount of energy dissipated during an extreme event is equal to the work (force times distance) done by the applied load as it moves through the displacement of the structure or element as the loading is applied and then removed, and is calculated as follows:

$$E_d = U_e = \int F(y)\,dy$$

where “y” is the bollard displacement and “F(y)” is the magnitude of the applied load at a displacement of “y” and E_d has units of Joules.



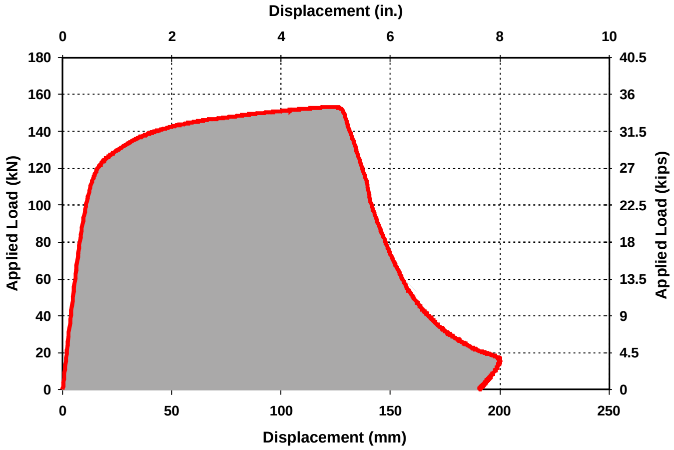
Thus, the energy dissipated by the bollard specimens is equal to the area under the load-displacement curves from the bollard tests, including the unloading portion of the curves.

The energy dissipated by each of the three bollard types was computed using the load-displacement response for the bollards tested under the rapid load rate (50 mm per sec.). The results are shown in Figure 9, where the energy dissipated is represented by the shaded area under each of the curves. All three of the tests under the rapid load rate where continued until an imposed displacement of 200 mm was reached. The full load-displacement curve up to the 200 mm displacement, and including the unloading portion of the curve, was considered when computing the energy dissipation.

The energy dissipated by the two plastic pipe bollards was approximately equal, with the steel-reinforced bollard dissipating slightly more energy that the GFRP-reinforced bollard. The steel pipe bollard dissipated approximately 8 times more energy than the plastic bollards due to its substantially greater strength.

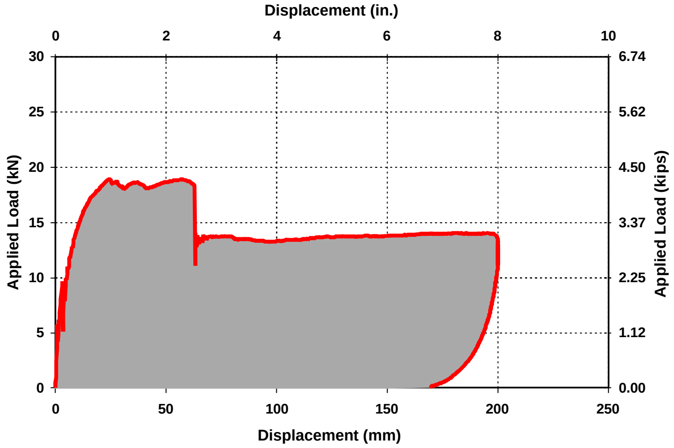
It is important to note that the energy dissipation figures are:

- Associated with failure of the bollard, and thus represent substantial damage to the bollard likely requiring complete replacement.
- Computed for the load rate of 50 mm/sec; other load rates will change the amount of energy dissipated by the bollards due to the strain-rate sensitive response of the materials.
- Based on test conditions where the bollard was rigidly fixed at its base; the energy dissipation capacities of the bollards will be affected by the actual installation conditions.



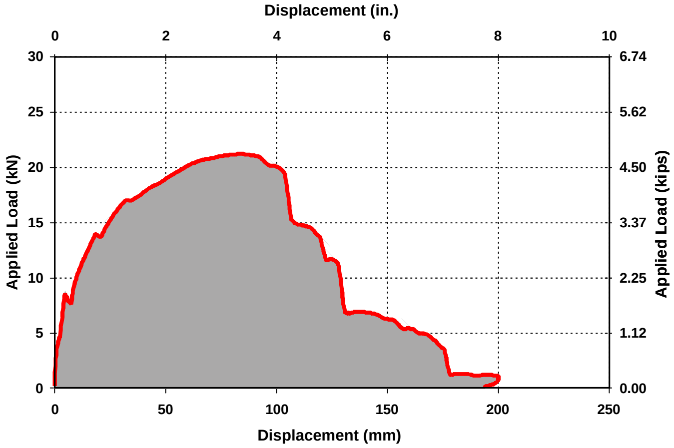
Steel Bollard

Energy Dissipation
(shaded area under curve)
= 21,570 J



Plastic Bollard with Steel Reinforcement

Energy Dissipation
(shaded area under curve)
= 2,850 J



Plastic Bollard with GFRP Reinforcement

Energy Dissipation
(shaded area under curve)
= 2,460 J

Figure 9 – Energy Dissipation for Bollards Tested Under Rapid Load Rate

Perspective – Significance of Results

The static strength and energy dissipation capacity of the steel pipe bollards are significantly greater than the two plastic pipe bollards tested. As expected, these results suggest that the steel pipe bollards have the ability to stop a much heavier and/or faster moving vehicle than the plastic pipe bollards.

In order to determine the ability of the plastic pipe bollards to stop a moving vehicle, a full-scale vehicle impact test must be conducted. Lacking these data, some insight to the ability of the bollards to stop a moving vehicle can be gained by comparing the kinetic energy of a moving vehicle to the energy dissipation capacity of the bollards.

The kinetic energy of a moving vehicle is equal to the amount of work required to stop the moving vehicle, and can be computed as follows:

$$E_K = \tfrac{1}{2} m v^2$$

where “m” is the mass of the vehicle (kilograms), “v” is the velocity of the vehicle (metres per second), and E_k has units of Joules.

The kinetic energy of a moving vehicle was computed for three vehicle sizes and vehicle velocities up to 15 km/hr (see Figure 10). A 1000 kg vehicle represents a compact car, a 1500 kg vehicle is typical of a mid-size car, while a 2500 kg vehicle represents a light truck. The energy dissipation capacities of the three bollard types are indicated in Figure 10 as horizontal lines.

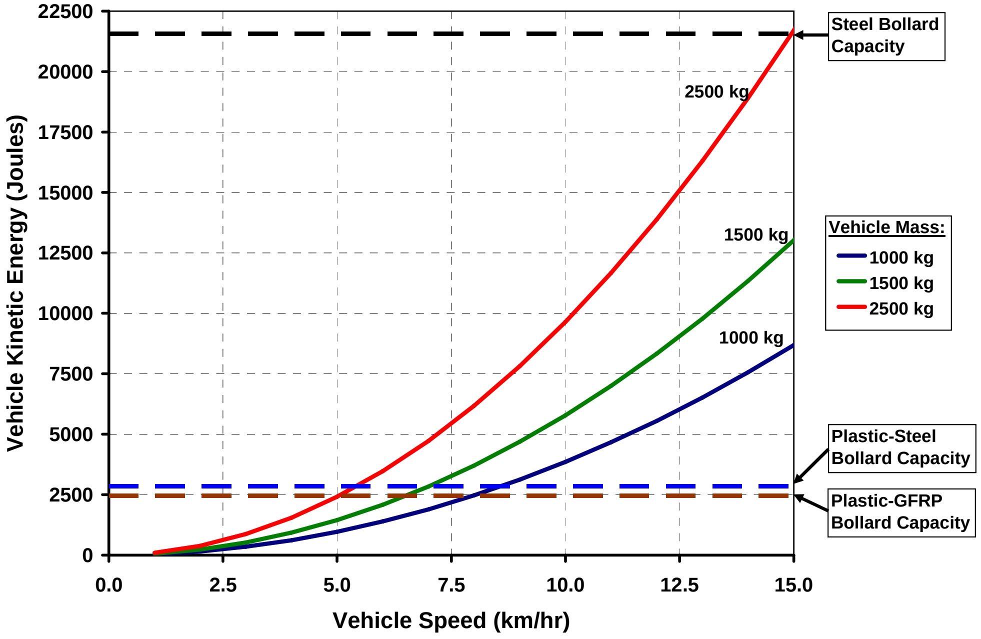


Figure 10 – Vehicle Kinetic Energy as a Function of Vehicle Speed

The data plotted in Figure 10 indicate that the energy dissipation capacities of the plastic bollards (approx. 2500 J) are comparable with the kinetic energy of a 2500 kg vehicle moving at 5 km/hr, or a 1000 kg vehicle moving at approximately 7.5 km/hr.

It is important to note that the data plotted in Figure 10 and the related discussion can not be used to determine the impact resistance of the bollards, nor can they be used to suggest application or safe-use limits for the bollards. A vehicle impact test utilizing the actual installation conditions for the bollards must be conducted to determine the vehicle impact limits for the bollards.

Closing

The following conclusions and observations summarize the findings of this testing program:

- The plastic pipe bollards with 2-10M steel reinforcing bars and those with 2-0.5 in. GFRP bars have a similar strength under static load conditions. The GFRP-reinforced bollards appear to be slightly stronger than the steel-reinforced bollards at higher load rates.
- The steel pipe bollards were approximately 8 times stronger than the plastic pipe bollards under static loading.
- The plastic pipe bollards with GFRP reinforcement have a smaller displacement capacity than both the plastic pipe bollards with steel reinforcement and the steel pipe bollards. That is, the plastic pipe bollards with steel reinforcement and the steel pipe bollards can deform more (approximately twice as much) before failure than the GFRP reinforced plastic pipe bollards.
- The plastic pipe bollards can recover approximately 50 mm (2 in.) of displacement upon unloading after failure, regardless of reinforcement type. The steel pipe bollards recovered less than 25 mm (1 in.) of displacement after failure.
- The plastic pipe bollards have a similar capacity for energy dissipation for both reinforcement types and amounts considered.
- The energy dissipation capacity of the steel pipe bollards is approximately 8 times greater than that of the plastic pipe bollards. These results indicate that the steel pipe bollards have the ability to stop a much heavier and/or faster moving vehicle than the plastic pipe bollards.
- The energy dissipation capacity of the plastic pipe bollards based on a loading rate of 50 mm/sec. is comparable to the kinetic energy of a 2500 kg vehicle traveling at 5 km/hr or a 1000 kg vehicle traveling at 7.5 km/hr. A vehicle impact test is required to determine the actual impact resistance of the bollards.

- The amount of steel and GFRP reinforcement considered in these specimens was relatively small. A larger area of reinforcement well distributed in the cross-section should improve the behaviour of the plastic pipe bollards.

The structures laboratory at the University of Waterloo is committed to excellence in research and testing. We hope that you are satisfied with the testing work conducted and that Sureguard Security Systems will consider the University of Waterloo for future research and advanced testing needs. Please contact us at your convenience should you have any questions or require any additional information.

Respectfully submitted,

Jeff West

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Project Researcher