Appendix C
DEBRIS IMPA"CT TESTS OF BLAZE-SHIELD *DC/F* SPRAYED FIRE-RESISTIVE MATERIAL

INTRODUCTION

This appendix presents experimental observations obtained from a series of debris impact tests on steel plates and bars with the sprayed fire-resistive material (SFRM) BLAZE-SIllELD DC/F. The tests were performed to provide evidence regarding the assumption that, within the debris field created by the aircraft impact into WTC 1 and WTC 2, the SFRM used for thermal insulation of structural members was damaged and dislodged.

Engineeringjudgment, based on the aircraft impact damage analysis (NIST NCSTAR 1-2), was used to develop test parameters that were also within the limitations of the experimental facility. Two sets of controlled experiments were designed: a high-speed low-mass test, which used uniform size lead pellets (buckshot) for debris and high-speed impact, and a low-speed high-mass test, which used a lower speed and several types of projectiles to simulate a random debris size distribution.

The SFRM on the steel plates and bars was subjected to a field of impacting projectiles fired from a universal receiver (a modified gun) at various orientations. For the high-speed low-mass impact, a debris field was simulated by buckshot fired from a modified shotgun. Since firing of conventional shotgun shells would result in average buckshot speed in excess of 682 mph (304 *mls),* controlled firing with custom-made shot shells was needed to reduce the impact speed within the range found for the debris field in the aircraft impact analyses of the WTC towers (NIST NCSTAR 1-2).

The speed of the aircraft at impact was estimated to be 443 mph (198 *mls)* for WTC 1 and 542 mph *(242 mls)* for WTC 2. Therefore, the speed of the debris field in each tower ranged between the maximum aircraft speed at impact and zero, when the debris came to a rest. As no single speed or debris size could represent the debris field in the towers, a range of debris speeds and sizes were selected that were within the limitations of the test facility, as noted above. An average speed of 341 mph (152 *mls)* was chosen for the debris impact velocity for the high-speed low-mass impact tests. For low-speed high-mass impact tests, an average speed of the projectiles ranging between 112 mph (50 *m/s)* and 201 mph (90 *mls)* was selected.

The desired impact speed was achieved but the universal receiver could only accommodate small projectiles, which did not represent actual debris shapes and sizes. Therefore, *the impact kinetic energies from the projectiles were significantly lower than those from actual impacting debris in the WTC towers due to differences in size (mass).* However, when the impact kinetic energies were normalized by the impact area, the impact conditions used in the tests approximated those in the towers, based on the following order-of-magnitude analysis.

The kinetic energies of the two aircraft before they impacted the WTC towers differed somewhat, but were of the same order of magnitude. Based on the aircraft masses and initial speeds reported in NIST NCSTAR 1-2, the kinetic energy of the impacting aircraft were approximately 3.4×10^9 ft lb (2.5×10^9 J)

and 5 x 10^9 ft lb (3.7 x 10^9 J) for WTC 1 and WTC 2, respectively. Based on the aircraft impact analysis (NIST NCSTAR 1-2), the speed of the aircraft fragments as they approached the core were about 0.4 to 0.7 of the initial impact speed for WTC 1 and WTC 2, respectively (energy is proportional to the square of the speed). In addition, portions of the aircraft masses were stopped prior to reaching the core. As a result, it might be expected that the energy associated with the aircraft debris at the core were on the order of 10^8 ft lb to 10^9 ft lb (10^8 J to 10^9 J).

For the purpose of this study, it was assumed that the energy of the debris impacting the SFRM was distributed throughout a debris area that was about five floors high (60 ft or 18 m) and 150 ft (45 m) wide, or an area of about 9 x 10^3 ft^2 (8 x 10^2 m^2). Thus, the energy per unit area would be on the order of $0(10^4$ to 10^5 ft $lb/ft^2)$ ($0(10^5$ to 10^6 $J/m^2)$). The total kinetic energy of the buckshot impact per unit area in the experiments was estimated, based on an average pellet size of 0.33 in. (8.4 mm), a mass of 0.1 oz (3.5 g), and a speed of 341 mph (152 *mls),* to be of the same order of magnitude, $0(10^4$ to 10^5 ft $lb/ft^2)$ ($0(10^5$ to 10^6 $J/m^2)$). Therefore, the impact parameters (impact speed and kinetic energy per unit area) used in the experiments are considered representative of these parameters in the aircraft impact analysis of the WTC towers. *However, the debris impact test condition simulated an instantaneous impact by a burst of debris whereas the actual scenario involved a three dimensional field of debris, with a depth, width, and height, continuously impacting the target(s) for a finite duration over a large area.* In addition, since the samples used in the tests were not restrained in the same way as actual structural elements would be, the response of the steel component and SFRM to debris impact in terms of dislodgement of SFRM may differ somewhat from that of an actual structural member.

EXPERIMENTAL APPARATUS AND TEST PROCEDURE

The experimental set-up and procedure used to perform the debris impact tests are described here. All ballistic tests on the SFRM were performed at the ballistic research test facility at NIST.

Ballistic research test facility

The facility consists of two pieces of ballistic firing equipment (small and large universal receivers), an optical device (two optical interrupters) to measure average projectile speed, an adjustable platform to mount the target, and a projectile trap. Figure C-I shows a schematic of the facility.

The small universal receiver was configured to a 12-gauge shotgun using a custom-made barrel. This universal receiver was remotely triggered in the adjacent control room. The shells used No. 00 lead buckshot with a diameter of 0.33 in. (8.4 mm). The shot shells were specifically tailored to achieve nominal average projectile speeds between 307 mph (137 *mls)* and 375 mph (168 *mls)* by adjusting the amount of gunpowder and the number of buckshot used in the shells. For all tests using the small universal receiver, 0.3 oz (10 g) of gunpowder (Hodgdon Titegroup) and 2 oz (63 g) of buckshot were used.

The large universal receiver was configured to have a custom-made barrel with an inside diameter of 3.15 in. (80 mm). The receiver was air operated and could be triggered only at the gun station. The shot shells consisted of two halves of Styrofoam wads that held 2.2 lb (1,000 g) of projectiles. The projectiles were comprised of a random combination of steel bolts and hexagon nuts that were larger and heavier than the buckshot (the largest nut size was 2 in. (50 mm) wide by 1.2 in. (30 mm) thick hexagon nuts for a 1 ¼ in. (32 mm) bolt). Air pressure was adjusted to achieve nominal average projectile speeds between

112 mph (50 *mls)* and 201 mph (90 *mls).* Thus, the large receiver simulated impact by fields of projectiles with larger mass density than those of the small receiver, but at slower speeds. Photos of the typical shot shells for ballistic impact tests using the large universal receiver are shown in Fig. C-2.

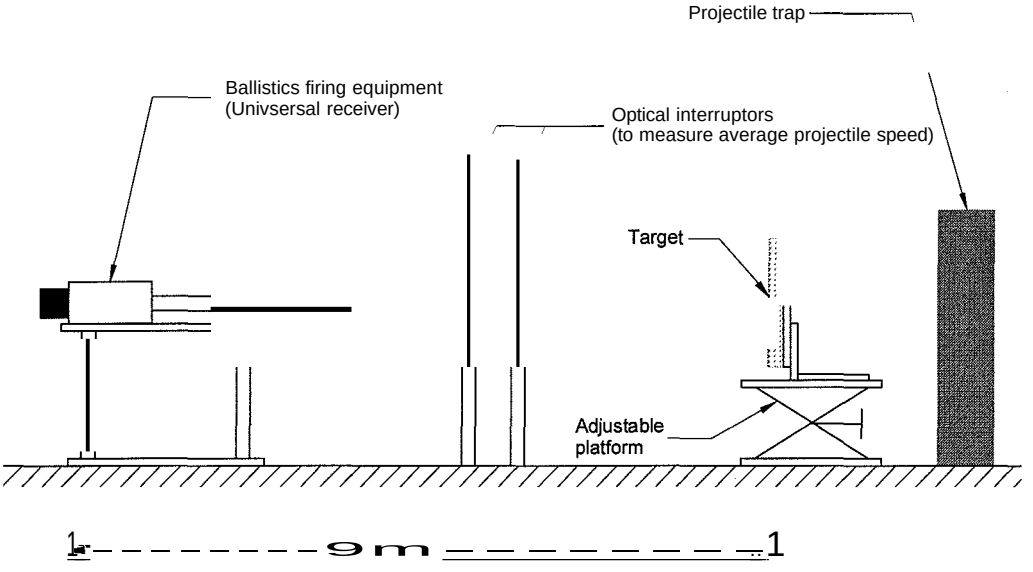

Figure C-1. Schematic of the ballistic research test facility.

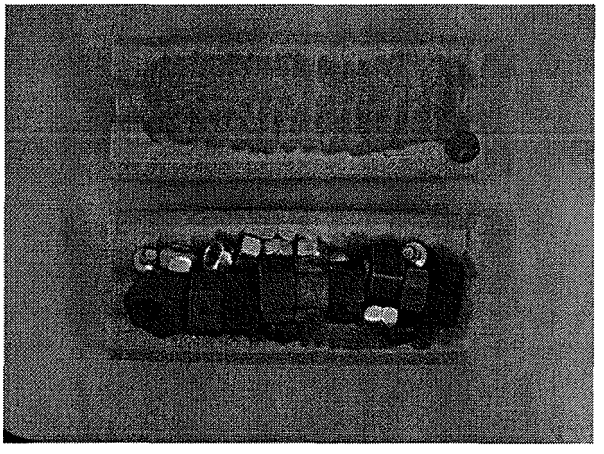

Figure C-2. Typical shot shells used in the large universal receiver. A penny is also shown for comparison.

The target was mounted 29.5 ft (9 m) from the universal receiver for testing of the steel plate specimens and 15.7 ft (4.8 m) for testing of the steel bar specimens. A plywood enclosure was built around the target area to contain ricocheted buckshot. A laser sight was used to position the target area with respect to the barrel. The impact angle was varied from a 0 degree (target perpendicular to the barrel) to 60 degree angle (measured from the 0 degree position).

Sample (impact target) preparation

The steel plates were ¼ in. x 12 in. x 12 in. (6 mm x 300 mm x 300 mm) and unprimed. Four nuts, arranged in a square pattern, 8 in. x 8 in. (200 mm. x 200 mm), were welded on one side of the plate to mount the sample for testing. The 1 in. (25.4 mm) diameter bars were 20 in. (508 mm) long for the small universal receiver tests and 36 in. (914 mm) long for the large universal receiver tests. The steel plates and the 36 in. long bars were shipped to Isolatek, Inc. in Stanhope, New Jersey, for application of BLAZE-SIllELD DC/F to a thickness of 1.5 in. (38 mm). The 20 in. (0.5 m) long bars had been previously prepared and sprayed by Isolatek at NIST with a nominal thickness of 1.5 in. (38 mm). Figure C-3 shows a steel plate with SFRM mounted in the ballistic research test facility ready for a test.

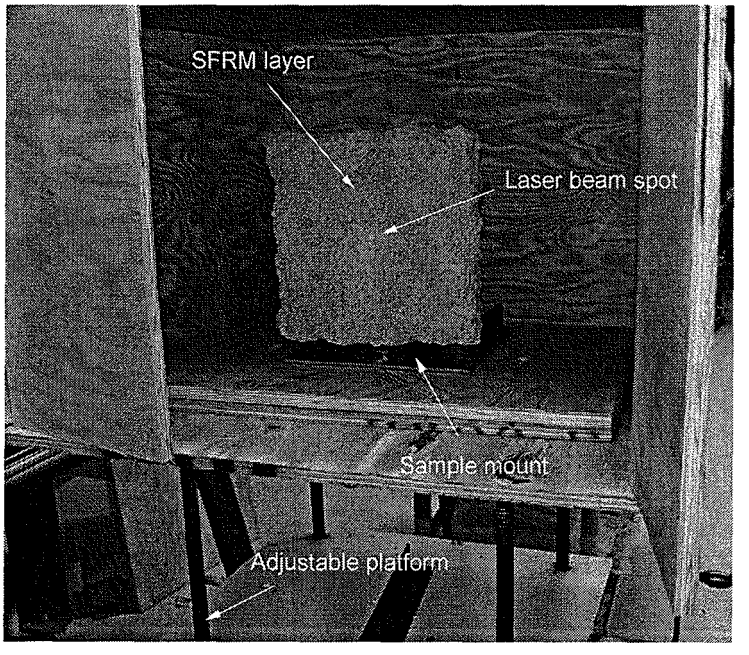

Figure C-3. Photograph of a steel plate with SFRM mounted in the ballistic research test facility.

Test matrix

Table C-1 summarizes the tests conducted in the debris impact tests.

Table C-1. Test matrix.

Debris speed/mass	Universal receiver	Test Specimen	Impact Angle				
			0°	*20°*	*30°*	*45°*	*60°*
High speed/low mass	Small	Steel plate (unprimed)	xxxx	xx		xx	xx
	Small	Steel bar (unprimed)	x				
	Small	Steel bar (primed)	xx				
Low speedlhigh mass	Large	Steel bar (unprimed)	xx				

'x' = 1 run

Test procedure

Each sample was photographed before and after each test. The steel plate or bar test sample was first mounted on two parallel L-brackets at the target location. The L-brackets were attached to a base plate, which could be rotated to adjust the impact orientation. A laser sight was then loaded into the chamber to center the target with respect to the barrel. The sample impact angle (0 degree, 20 degree, 30 degree, 45 degree, or 60 degree) was set using a protractor. Impact angle was measured with respect to the leading edge of the adjustable platform, which was set to be perpendicular to the laser beam. A 0 degree impact angle was defmed as the target oriented perpendicular to the direction of the projectiles. Other impact angles were measured with respect to 0 degree.

After the impact angle was set, the laser sight was removed from the chamber of the barrel. The shot shells were prepared in the ammunition laboratory. The receiver was fired and the average projectile speed was recorded. The impact tests were viewed through a bulletproof observation window in the control room. After the test, the sample was examined and photographed to assess damage to the SFRM by the projectiles.

The nominal impact area by the buckshot fired from the small universal receiver at a distance of 29.5 ft (9 m) had a diameter of approximately 6 in. to 8 in. (0.15 m to 0.2 m). For the large universal receiver, the nominal impact area by the projectiles (bolts, nuts, and buckshot) had a diameter of approximately 24 in. (0.6 m). For the steel bars, the impact area was reduced to about a 4 in. (0.1 m) diameter, which was approximately the diameter of the SFRM layer on the bar, by moving the bar closer to the receiver to increase the likelihood of projectiles hitting the target.

TEST RESULTS AND DISCUSSION

In this section, damage to the SFRM due to debris impact is assessed and photographic evidence is provided.

Steel plate and SFRM specimens

All tests on steel plates were performed using the small universal receiver (high-speed low-mass). In these tests, the impact area was much smaller than the sample surface area. Table C-2 summarizes the test parameters for the steel plates with an SFRM layer. The kinetic energy per unit impact area was estimated based on the projectile speed, an average pellet mass of 0.1 oz (3.5 g), and an impact area equivalent to the cross section area of the pellet 0.09 in^2 (5.52 mm^2). Tests at a 0 degree impact orientation had damage to the SFRM at the points of projectile impact, which was marked by distinct, approximately circular indentations on the layer. The vibration of the plate caused by the impact was severe enough to break the adhesive bond and completely separate the SFRM from the unprimed steel plate (see Figure C-4). Similar observations were made for tests at a 20 degree and 40 degree impact angle, as shown in Figure C-5 and Figure C-6, respectively. However, at a 60 degree impact orientation, the SFRM remained attached to the steel plate. Several projectile exit points were noted, which were due to projectiles ricocheting off the steel surface. Figure C-7 shows the entry points of the projectiles and the damage to the SFRM, and illustrates the size of the debris impact field relative to the specimen size. Two Odegree impact tests were also conducted with the four edges of the SFRM layer taped to the steel plate (see Figure C-8) to simulate better adhesion to the plate and to prevent the separation of the SFRM from

the plate upon impact of the projectiles. However, when the tape was carefully removed after the test, no adhesion of the SFRM to the steel plate was found; this also occurred for the 0 degree impact test without duct tape.

Table C-2. Summary of test parameters for using unprimed steel plates with SFRM.

Test #		Impact orientation (degree)	Average projectile speed (fils (m/s»	Kinetic energy per impact area (fi lb/ft² (J/m²)»
Small universal receiver (low mass, high impact velocity)	PL01	0	511 (155.8)	5.3 x 10^4 (7.7 x 10^5)
	PL02	55	346 (105.5)	2.4 x 10^4 (3.5 x 10^5)
	PL03	60	574(175)	6.7 x 10^4 (9.7 x 10^5)
	PL04	0	541(165)	5.9 x 10^4 (8.6 x 10^5)
	PL05	20	469(143)	4.5 x 10^4 (6.5 x 10^5)
	PL06	20	563 (171.6)	6.4 x 10^4 (9.3 x 10^5)
	PL07	40	561(171)	6.4 x 10^4 (9.3 x 10^5)
	PL08	40	568(173)*	6.5 x 10^4 (9.5 x 10^5)
	PL09**	0	558(170)	6.3 x 10^4 (9.2 x 10^5)
	PLIO ••	0	225 (69)	1.0 x 10^4 (1.5 x 10^5)

* Receiver misfired initially at 102 ft/s (31 *mls),* a few shots hit but there was no visible damage to SFRM, sample reused for 2nd shot.

•• The edges of the SFRM layer were taped to the steel plate using duct tape.

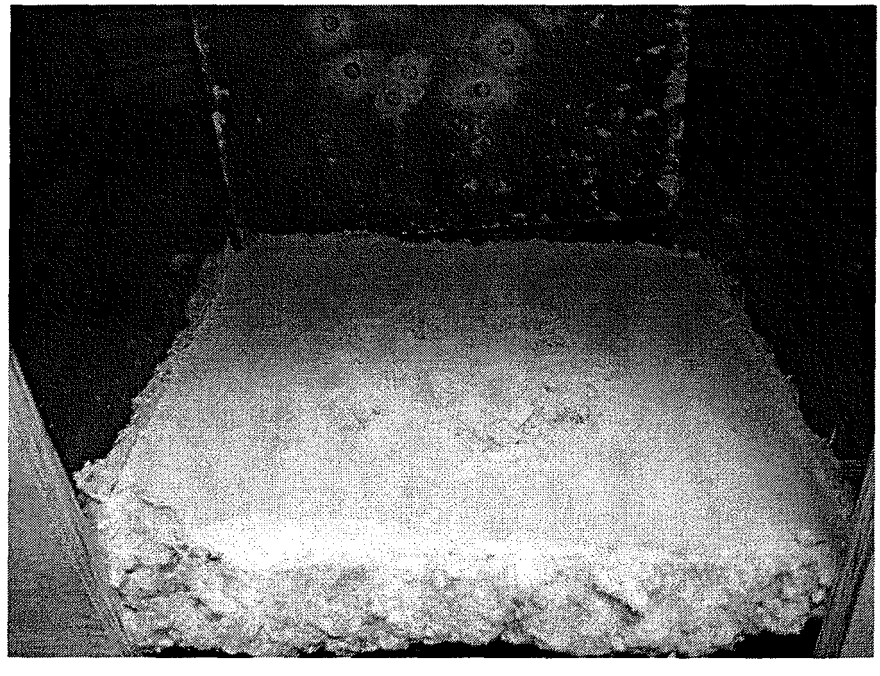

Figure C-4. Photograph showing damage to the SFRM after a ballistic impact at 0 degree. The SFRM layer completely separated from the steel plate.

Figure C-5. Photograph showing damage to the SFRM after a ballistic impact at 20 degree. The SFRM layer completely separated from the steel plate and landed on the floor.

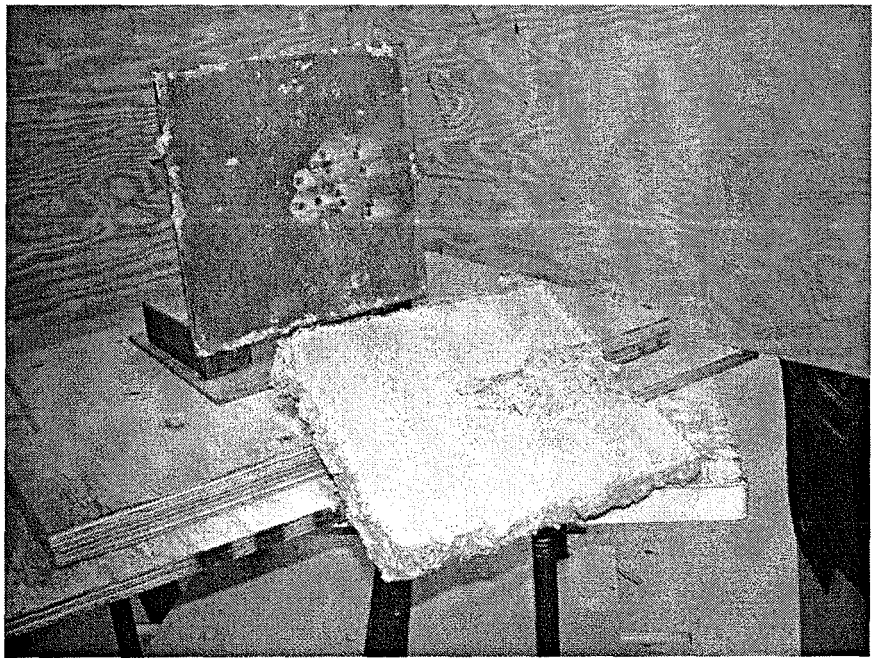

Figure C-6. Photograph showing damage to the SFRM after a ballistic impact at 40 degree. The SFRM layer completely separated from the steel plate.

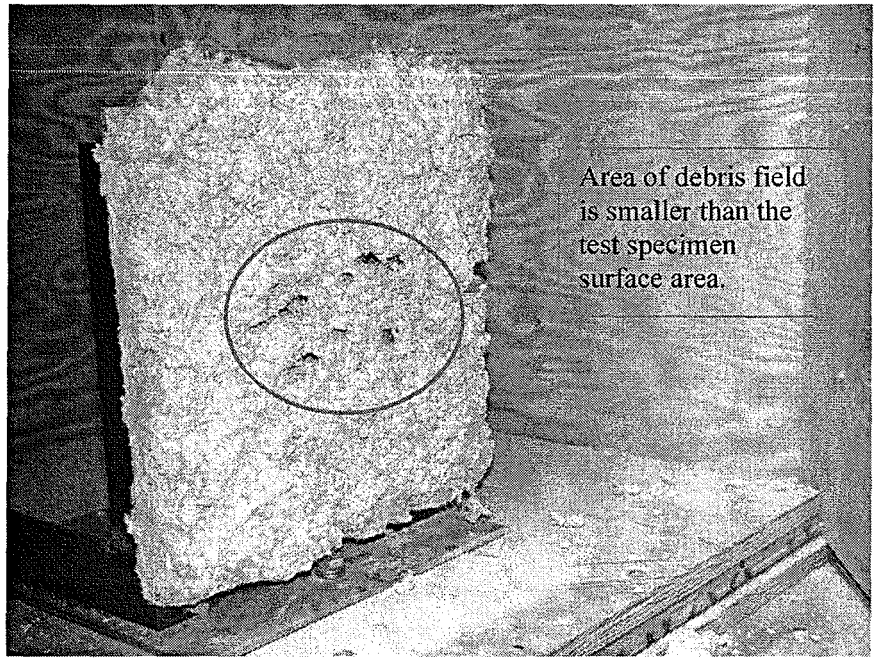

Figure C-7. Photograph showing damage to the SFRM after a ballistic impact at 60 degree. The SFRM layer did not separate from the steel plate.

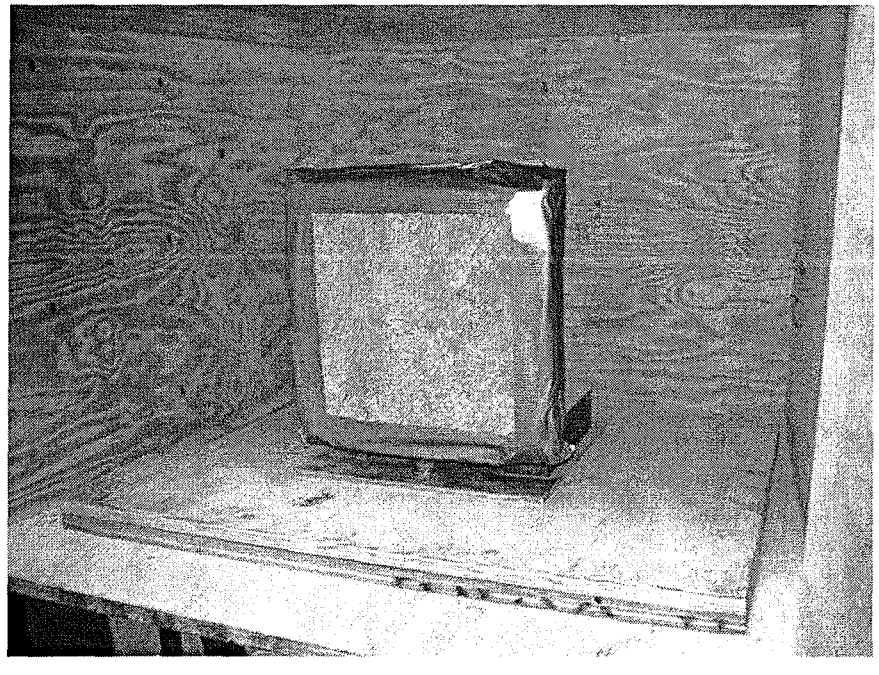

Figure C-8. Photograph showing the edges of the SFRM duct taped to the steel plate before the ballistic tests at 0 degree.

Steel bar and SFRM specimens

The ballistic impact tests for the steel bars were performed using both the small and large universal receivers. A summary of the test parameters used for the steel bars with SFRM is given in Table C-3. For these tests, the adjustable mounting table was moved closer to the receiver to reduce the number of projectiles that might have missed the target bar. The distance from the chamber of the universal receivers to the target was 15.7 ft (4.8 m).

In tests using the small universal receiver (high-speed low-mass), the projectiles dislodged the SFRM completely at the impact area of both the primed and unprimed bars, exposed the steel bar, and resulted in loss of adhesion (not cohesion) of the remaining SFRM on the bar. After the ballistic impact, the remaining SFRM rotated freely with respect to the bar. Figure C-9 and Figure C-10 show the damage to the SFRM on the unprimed and primed bars, respectively, which were tested with the small universal receiver. In Figure C-9, the projectiles impacted the upper portion of the bar specimen and missed the center and lower portions.

Similar results were observed for tests with the large universal receiver (low-speed high-mass). The projectiles dislodged the SFRM completely at the impact area of the bars, resulting in exposed steel bar and loss of adhesion of the remaining undamaged SFRM on both sides of the impact area. Figure C-11 and Figure C-12 show the damage to the SFRM on unprimed steel bars tested with the large universal receiver. In Figure C-12, the projectiles also missed the lower portion of the specimen.

Table C-3. Summary of test Parameters used for the steel bars with SFRM

	Test #	Configuration	Impact orientation (degree)	Total mass of projectiles (oz (g))	Average projectile speed *(ft/s (m1s))*	Kinetic energy / impact area (ft **lb/ft²** *(J/m²)*)
Small Universal Receiver	BAROI	unprimed	0	2 (63)*	443 (135)	4.0×10^4 (5.8×10^5)
	BAR02	primed	0	2 (63)*	556(170)	6.2×10^4 (9.1×10^5)
	BAR03	primed	0	2 (63)*	543 (166)	5.9×10^4 (8.7×10^5)
Large Universal Receiver	BAR04	unprimed	0	32 (1,000)**	282 (86)	3.2×10^4 - 5.3×10^4 (4.6×10^5 - 7.8×10^5)
	BAROS	unprimed	0	32 (1,000)**	344 (105)	4.6×10^4 - 8.0×10^5 (6.8×10^5 - 1.2×10^6)

* Projectiles consisted of only No. 00 lead buckshot.

** Projectiles consisted of a combination of hexagon steel nuts of different sizes. The minimum and maximum kinetic energy per unit impact area were estimated based on the smallest and the largest nuts and the minimum and maximum nut cross sections as impact areas.

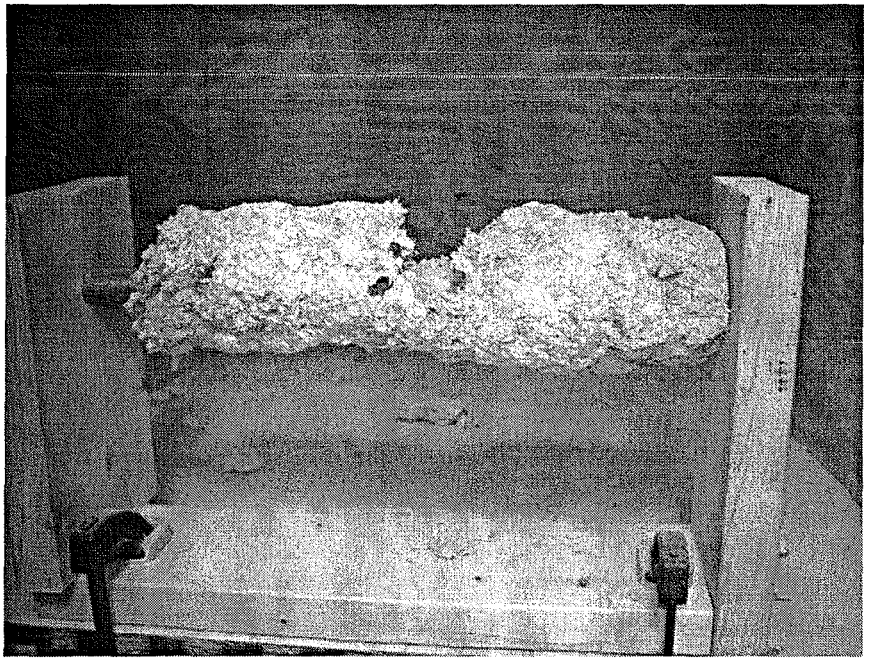

Figure C-9. Photograph showing damage to the SFRM on an unprimed steel bar (BAR01) after a ballistic impact at 0 degree using the small universal receiver.

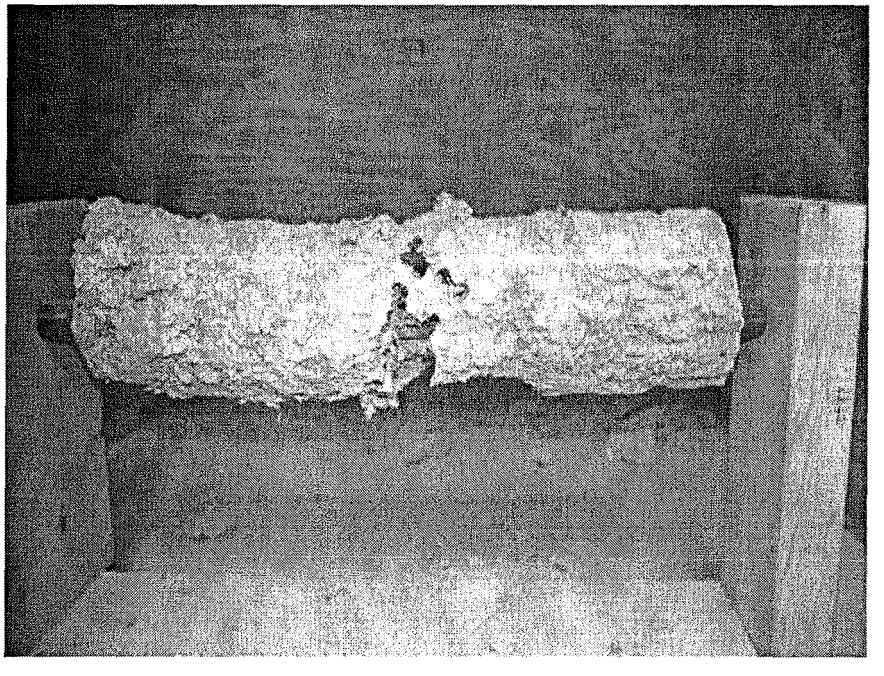

Figure C-10. Photograph showing damage to the SFRM on a primed steel bar (BAR02) after a ballistic impact at 0 degree using the small universal receiver.

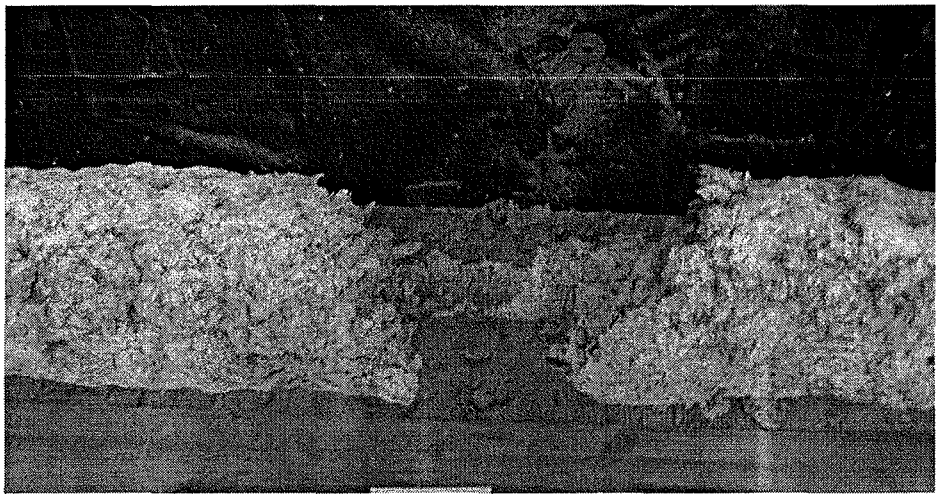

Figure C-11. Photograph showing damage to the SFRM on unprimed steel bar (BAR04) after a debris impact at 0 degree using the large universal receiver.

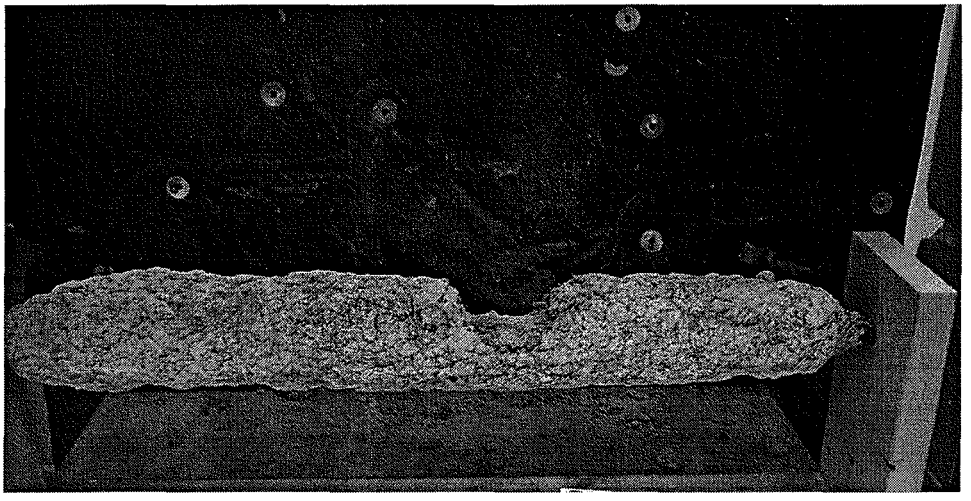

Figure C-12. Photograph showing damage to the SFRM on unprimed steel bar (BAR05) after a debris impact at 0 degree using the large universal receiver.

SUMMARY OF FINDINGS

Based on the observations made in the ballistic impact tests, the SFRM was dislodged by direct impact with solid objects that had a kinetic energy per unit impact area approaching 10^4 to 10^5 ft lb/ft^2 (10^5 to 10^6 J/m^2). In addition, SFRM that was not dislodged after the debris impact lost its adhesion to the steel surface in all but one test. The SFRM on the steel plate was dislodged upon impact of the projectiles, except for the ballistic impact at a 60 degree angle to the plate. When the SFRM was taped to the steel plate and the tape carefully removed after debris impact at 0 degree, no adhesion of the SFRM to the steel plate was found, the same result found for the 0 degree impact test without duct tape. For SFRM on steel bars, the remaining SFRM after impact rotated freely with respect to the bar.

When the debris field dimensions were similar to the specimen dimensions, the SFRM was dislodged completely from the steel component. For instance, the SFRM was dislodged over the width of the steel bar specimen when the debris field was centered over the specimen width. However, the steel plate dimensions were much larger than the debris field dimensions and the SFRM was damaged only where the impact occurred; the surrounding SFRM remained cohesively intact but lost its adhesive bond to the steel plate.

The test results demonstrated that there was dislodgment of SFRM at locations subject to direct debris impact. For direct debris impact up to a 60 degree orientation, the SFRM adhesive bond to the steel component was lost, but there was no loss of the SFRM cohesive bond.

In the WTC towers, where the debris fields were larger than the dimensions of steel components (Le., such as trusses, beams, and columns), these tests show that SFRM would have been dislodged for a wide range of debris sizes and speeds. The test results support the assumption that, within the debris field created by the aircraft impact into WTC 1 and WTC 2, the SFRM used for thermal insulation of structural members was damaged and dislodged.