HARPOON TECHNOLOGY DEVELOPMENT FOR THE ACTIVE REMOVAL OF SPACE DEBRIS

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This paper presents the results of empirical testing and numerical modeling carried out to demonstrate the effectiveness of a harpoon as an Active Debris Removal (ADR) device. The parameters tested include: the relationship between tip shape and both ballistic limit and the creation of secondary debris; the ability to penetrate targets at oblique impact angles, low temperature and with heat pipe obstructions; the ability to lock onto targets post-penetration and withstand the loads expected during de-orbiting maneuvers; and the effect of tip shape on the penetration of CFRP targets. Testing involving the impact of blunt and conical shaped steel tips into 3mm aluminium (Al) plate showed that the ballistic limit varies in proportion to the tip circumference, with conical shapes having a higher relative ballistic limit due to the additional energy required for petalling. In regards to secondary debris, it was found that blunt shapes created a plug during penetration as a result of shearing around the periphery of the projectile, whilst conical tips resulted in minor spalling and fragmentation. Preliminary oblique impact testing up to 40° showed that the ballistic limit increases with obliquity at a greater rate for blunt tips than conical ones. This was supported by simulations up to a 60° impact angle. Impact testing of 3mm Al plate with conical projectiles at low temperatures showed a more brittle fracture mode when compared with targets impacted at room temperature. This resulted in a cleaner fracture surface and an increased ballistic limit. Impact testing of Al panels obstructed with fixed heat pipes showed that the harpoon could successfully penetrate a target panel with such an obstruction due to shearing of the pipe flange. Testing of two lock-on mechanisms showed that both a spring activated and integrated toggle could reliably open on target penetration. Tensile load testing was also conducted and showed that both designs could withstand the loads expected during de-orbiting maneuvers, with the integrated toggle being more robust. Simulation was used to evaluate the effect of varying the diameter of a conical tip on the ballistic limit. The results showed that the ballistic limit increased with diameter. Finally, a Smooth Particle Hydrodynamics (SPH) solver, which is better suited to modeling impact into brittle materials, was used to model impact into CFRP targets. This showed that, in comparison with blunt tips, conical tips had a higher ballistic limit. In addition, the debris formed was less coherent and had a higher terminal velocity. Further simulation showed that numerical modeling can provide an accurate prediction of the ballistic limit for Al plate impacted by conical projectiles, excellent prediction of impact failure modes, good predictions of debris likely to be created during the impact process, and an efficient means of testing prototype tip shapes.

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I. Introduction

Current estimates suggest that approximately 5,500 metric tons of space debris, comprised of spent rocket bodies, decommissioned satellites, and other disused material is orbiting the Earth (Astrium, 2012). Apart from the obvious threat that this quantity of debris presents to both manned and unmanned equipment in orbit, an additional threat of uncontrolled, cascading collisions, commonly referred to as the Kessler syndrome (Nikolaev, 2012), also exists. The harpoon is one of several Active Debris Removal (ADR) systems currently being investigated by the ESA to interrupt this potential cascade of collisions by removing large, uncontrolled debris (Astrium, 2012). The research undertaken as part of this project aims to contribute to studies being conducted by Airbus Defence & Space on the viability of using a harpoon in an ADR role.

In order for a harpoon to be used successfully in an ADR role it must meet several requirements. The first of these includes being able to penetrate a target with minimal energy and creation of secondary debris. In regards to the former, minimising required impact energy reduces the propellant needed to launch the harpoon. This reduces the overall mass of the ADR system and would not be insignificant in the likely event that multiple harpoons are launched on a single spacecraft. In addition, as will be identified in this paper, reducing impact energy also reduces the creation of secondary debris. This not only reduces the risk of adding to the space debris problem, but also damaging vulnerable equipment within the target. This could include fuel and heat pipes, as well as pressure vessels and batteries. Penetration of any of this equipment could lead to fragmentation or explosions (Schaefer et al., 2008). Performance against this requirement was assessed by undertaking experimental tests to establish a relationship between tip shape, ballistic limit and secondary debris creation. In addition, tip parameterisation was undertaken using simulation methods to reduce the quantity of experiments required.

The second requirement identified was that the harpoon must be capable of penetrating a range of target materials under a variety of conditions and in different configurations. The materials include those that are typically found on solar arrays (CFRP, and 20mm Al core with 0.25mm CFRP skin), and equipment panels and payload adaptors (3-5mm Al panels or Al Sandwich panels with 0.5mm thick skin) (Astrium, 2012). Whilst penetration of Al and Al honeycomb (Al H/C) panels was tested experimentally, due to the limited availability of CFRP, the effectiveness of different tip shapes against this material was compared using simulation. In regards to target conditions, its temperature could vary significantly depending on its orientation in relation to the sun at the time of impact. This could have a significant effect on the properties of the target material. As a result, impact testing on Al targets cooled to very low temperatures was conducted to determine the effect of extreme cold on the ballistic limit of Al plate as well as the creation of secondary debris.[2] In regards to target configuration, this relates to panels which may be obstructed by equipment boxes and/or attached heat pipes. Heat pipes in particular are a significant consideration as they typically have a 3mm wall thickness (Astrium, 2012). As such, impact tests were conducted on target panels fitted with representative heat pipes to determine the effect of such obstructions on harpoon penetration. Target configuration also relates to its orientation at the time of impact. As potential targets could be spinning or tumbling, impact is likely to occur at an oblique angle.

[2] Temperature of orbiting objects such as the ISS varies between -128°C in eclipse to 93°C in direct solar radiation, http://www.nasa.gov/content/cooling-system-keeps-space-station-safe-productive/#.U3BVvvmSyuI, viewed on 10 May 14

Limited impact testing was therefore conducted on targets up to an angle of obliquity of 40°. This limited experimental testing was supplemented by simulating impacts up to an angle of 60°.

The final requirement identified relates to the lock-on mechanism used to securely attach the harpoon to the target to facilitate stabilisation and de-orbiting maneuvers. The forces generated during this phase of the mission are expected to average approximately 500N, with a peak as high as 2-3kN in the event of a high thrust de-orbit manoeuvre (Astrium, 2012). Testing of two different lock-on mechanisms to confirm reliability of deployment as well as load capacity was therefore conducted.

II. Experimental Set-Up

The UNSW medium velocity gas gun was used to conduct the experimental component of this study. This gas gun was chosen as it was able to impart the estimated energy required to allow the projectile to penetrate the thickest target configuration tested. Projectile speed was initially measured using two sheets of Al foil spaced a given distance apart and connected to an Arduino microcontroller. The timer was triggered as the projectile broke through each piece of foil. This method proved to be highly inaccurate however due to the inconsistent flexing of the foil pieces prior to projectile penetration. As a result, a modified speed sensor using two infrared sensor/transmitter pairs was developed. This enabled the time of flight between the two sensor pairs to be measured to a resolution of 1×10^{-6} sec. This set-up was positioned at the bore exit and is detailed in Fig. 1.

All target plates used during the impact experiments were 250mm^2 in dimension and varied in thickness. These were secured to a target box which was positioned on a steel frame. In order to decrease experimental uncertainty due to target movement upon impact, the plates were attached to the target box with two 6mm thick Al holders which were bolted to a 4mm thick steel adapter plate. This adapter plate was secured to the box with M10 bolts. The box itself was filled with clay and bolted to the stand. In order to further reduce the chance of movement, solid steel plates were placed behind and on the target stand. This set-up can be seen in Fig. 2. This configuration was later modified for impact testing of obstructed panels. The target box was removed and the target adapter plate fixed directly to a steel frame. This configuration allowed high speed video footage to be taken of the rear of the target during impact and therefore the nature of heat pipe failure to be recorded.

The harpoon used for experimental testing was manufactured from 10mm diameter mild steel rod. Several iterations were developed to improve reliability against failure. Whilst the initial version was modular to allow replacement of harpoon segments in the event of failure, or to change its length, it was found that this design actually contributed to failure on impact. The final version was therefore manufactured from a single threaded rod. The thread enabled the fitting of different attachments such as non-discarding sabots as well as damper systems. The end of the harpoon was threaded to allow for the fitting of different tips. These tips were also manufactured from mild steel and were drilled and tapped with a 3/16 thread. This thread size was chosen as it corresponded to that used in the *Ramset* toggle trialed as a lock-on device. The harpoon and tips are shown in Fig. 3.

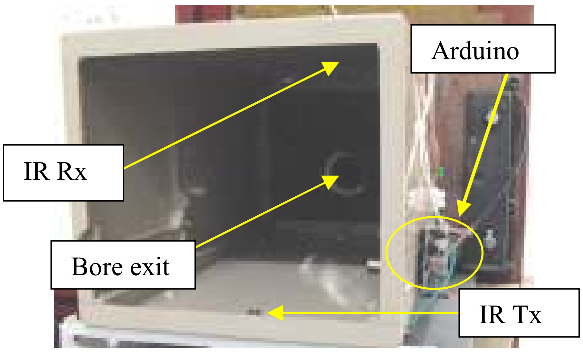

Figure 1. Sensor used to measure harpoon speed.

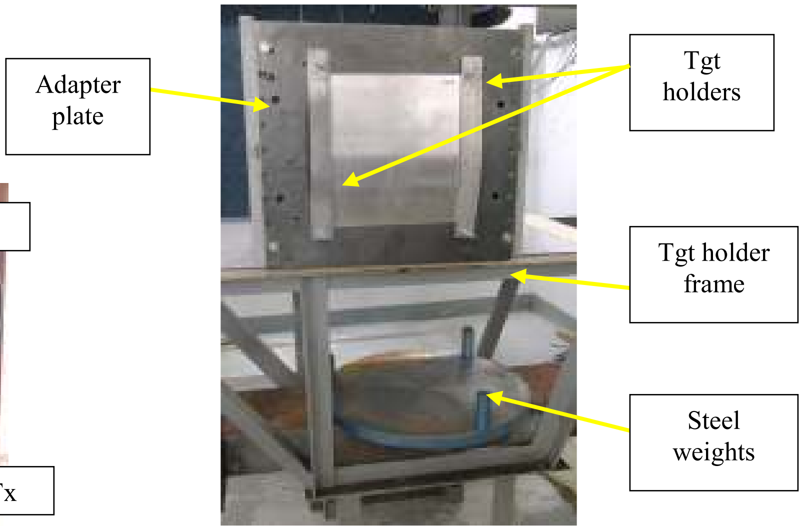

Figure 2. Target holder set-up used for ballistic limit and oblique impact testing.

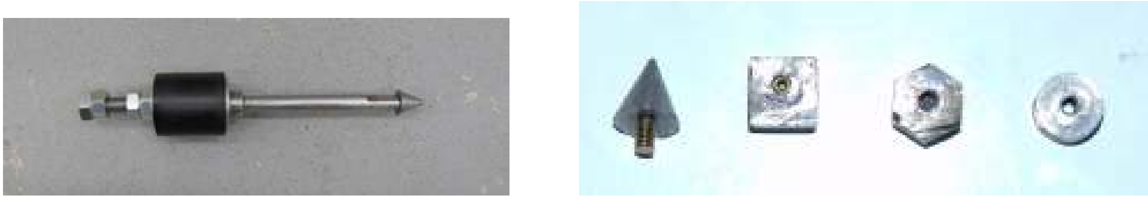

Figure 3. Harpoon used for experimental testing (left) and tips used for ballistic limit comparison (right).

III. Results and Discussion

A. Ballistic Limit Testing

The ballistic limit of 3mm, Al5005H34 plate for both conical and blunt tip shapes was determined experimentally. Specifically, the purpose of this testing was to identify which tip shape had the lowest limit as, in addition to reducing the propellant required, minimising the ballistic limit will reduce the shock-induced stresses in the target material. This is important as it reduces the risk of spalling and therefore further debris creation. Whilst spalling is commonly associated with the tensile stresses resulting from the reflection of shock waves from the free surface of a target (Meyers, 1994), it can also occur through a process known as ductile spall damage. This is particularly relevant for Al. This process leads to the development of spall as a result of void nucleation and growth (Meyers, 1994). As the likelihood of damage is a function of the magnitude of the shock-induced stress in the target material, reducing the impact energy is likely to reduce the onset of ductile spall damage.

Potential errors associated with the testing regime include deflection of the target box and adapter plate as a result of the high impact energy, and the anisotropic nature of the target material. In regards to the latter, yield strength will vary depending on the orientation of the grains in a given sample. In regards to deflection, as discussed in the introduction, this was minimised by mounting the target securely to the target box. Resultant deflection was recorded using a high speed camera at 1200 frames per second. From the footage it could be seen that deflection occurred post impact rather than during penetration as a result of shock wave propagation through the target and box, as well as the inertia of the target set-up. As a result, the effect on recorded ballistic limits is evaluated as minor.

The results of the experimental ballistic limit testing, including uncertainty ranges, are detailed in Table 1. The upper limit corresponds to the velocity at which complete penetration occurred, while the lower limit represents the closest recorded velocity below this value at which full penetration did not occur. From these results it can be seen that, with the exception of the cone, the ballistic limit is proportional to the circumference of each tip.

Table 1: Ballistic Limits for 3mm Al5005H34 Plate Impacted by Different Harpoon Tip Shapes

Tip Shape	Dimensions (mm, deg)				Ballistic Limit (m/s)	Kinetic Energy (J)	$\left(\frac{E_{i,ave}}{E_{cone,ave}}\right)$
	Dia.	Length	Angle	Circ.			
Cone	16	18	24	49	42.9 - 44.2	206.8 - 220.3	1.0
Cube	N/A	16 (side length)	N/A	64	40.9 - 42.2	204.1 - 217.1	0.99
Hex	N/A	16 (across flats)	N/A	54	38.6 - 40.3	190.41 - 207.8	0.93
Cylinder	16	11.5	N/A	50	33.3 - 35.5	128.4 - 145.8	0.64

The fact that the ballistic limit of the cone deviates from this trend can be explained by the difference in failure modes of blunt versus conical tips. Perforation of plates by blunt or rounded projectiles 'usually involves punching out a plug resulting from shear failures that initiate along or near the boundary of the impact surface' (Goldsmith & Finnegan, 1986), however, perforation by conical or ogive tips results in piercing, crack propagation and petaling (Levy & Goldsmith, 1984). As the latter involves high radial and circumferential tensile stresses (Zukas, 1982), more energy is required.

B. Secondary Debris Creation

As the intent of the harpoon system is to remove debris from low earth orbit, this study also included an assessment of the relative amount of debris created by each tip shape. From this testing, it was confirmed that impact of thin Al targets with conical tips can produce ductile spalling and minor fragmentation. Impact by

blunt tips can produce plugs, and occasionally minor fragmentation. Of note, any debris produced during the experimental impact tests was opposite to the side impacted, which would typically be internal to the debris object. Examples of the debris produced by blunt and conical tip shapes are given in Fig. 4.

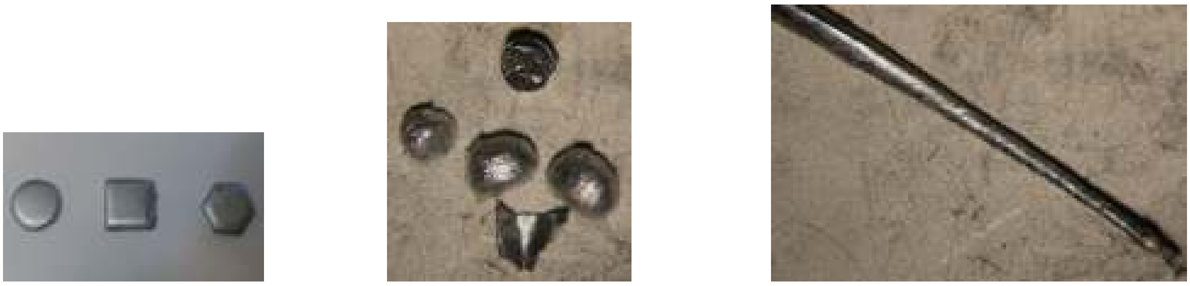

Figure 4. Plugs produced from impact of 3mm Al5005H34 plate by blunt projectiles (left) noting that dimensions match those of respective tips given in table 1. Spall (centre) and fragmentation (right) produced from impact of 3mm Al5005H34 plate by conical and blunt projectiles respectively at 8x magnification. Maximum spall diameter (centre) is 2.6mm. Fragmentation dimensions (right) are 15.2mm long, 0.6mm wide.

Of note, in regards to impact into spacecraft, unless the impact site is a radiator panel or solar array most of the structure will be covered with MLI and this has been shown to help trap inside the satellite any small particles created during the harpoon impact. (Reed & Barraclough, 2013).

C. Low Temperature Impact Testing

Although published data was not available for Al5005H34, the tensile strength of Al2024, commonly used in space applications, has been shown to increase by approximately 276MPa over a temperature range of room temperature to -269°C. In addition, the % elongation and ductility of some Al alloys decreases with a significant reduction in temperature (Hickey, 1962). The reason for this testing therefore was to investigate the effect of low temperature on the ballistic limit and, more importantly, to investigate whether the increased brittleness of Al at these temperatures would increase the risk of secondary debris creation.

The low temperature testing was conducted on 3mm Al5005H34 plate using a conical tip. The target material was cooled to -171°C by immersion in liquid nitrogen before being impacted by the harpoon with the temperature of the target being monitored with a K-type thermocouple. Due to the time delay between removing the target from the liquid nitrogen and firing the gun, the target temperature increased prior to impact. It is estimated that an uncertainty of approximately 5°C exists in the impact temperature readings. This is due to the fact that only one thermocouple was placed at the base of the target and uniform temperature across the target plate cannot be assumed. The recorded impact temperatures as well as the results of this experiment are detailed in Table 2.

Table 2: Results From Impact of a Conical Projectile Into 3mm Al5005H34 Plate at Low Temperatures

Test	Impact Energy(J)	Impact Temperature(°C) +/-2°C	Perforation diameter(mm) +/-0.5mm
1	247	-104	14.5
2	255	-83	16
3	255	-119	13.5
4	265	-102	16
5	265	-86	Complete penetration
6	148	-107	12.6
7	241	-130	13.6
8	217	-138	12.2
9	202	-136	12.7
10	202	-132	13.1
11	224	-80	14

From these results it can be seen that for the same impact velocity e.g., data points four versus five and nine versus ten, the penetration depth decreases with decreasing temperature. In addition, although the impact

velocity for test four was 20% higher than the ballistic limit for the Al impacted at room temperature, complete penetration did not occur. This provides good evidence that the ballistic limit of Al plate increases with low temperature. This correlates well with the increase in strength at low temperatures noted in the aforementioned research.

As well as increasing the ballistic limit, cooling Al plate to low temperatures resulted in reduced spall and fragmentation of the target plate. This difference is likely to be the result of the reduction in ductility with temperature of the sample. This reduction in ductility reduces the likelihood of ductile spalling mentioned earlier. Photographs of two impacted samples, taken at 8 x magnification, show a clear difference in the fracture surface of Al plate impacted at room temperature in comparison to that impacted at low temperatures. The sample shown in Fig. 5 was impacted at room temperature at a velocity of 42.2m/s resulting in a perforation diameter of 14.5mm. The sample shown in Fig. 6 was impacted at -119°C at 47.3m/s resulting in a perforation diameter of 13.5mm. Fig. 5 shows the onset of spalling (arrow) as well as the formation of fragmentation (circled), however, Fig. 6 shows relatively clean fracture surfaces. From this testing it can therefore be concluded that, whilst impacting Al alloy targets at low temperatures may require a slight increase in impact energy, the potential for additional debris formation may actually be reduced.

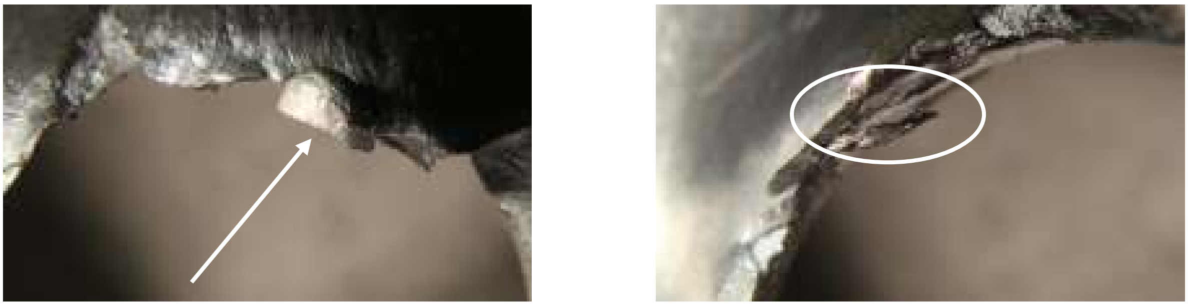

Figure 5. Fracture surface of 3mm Al5005H34 plate impacted at room temperature at 8 x magnification (left). The onset of spall formation is evident in centre right of image. Fracture surface of 3mm Al5005H34 plate impacted at room temperature at 8 x magnification (right). Formation of fragmentation is evident in centre left of image.

Figure 6. Fracture surface of 3mm Al5005H34 plate impacted at -119°C at 8 x magnification.

D. Heat Pipe Obstruction

In the event that the harpoon is used as an ADR system, it is unlikely that it will penetrate a completely unobstructed panel. Potential targets such as satellites will commonly have heat pipes as well as equipment boxes fitted. As such, it was deemed important to obtain empirical results for impact into panels fitted with such obstructions. Impact testing was therefore conducted to determine the ability of the harpoon to penetrate 2mm thick Al6061-T6 plate with a representative heat pipe secured to the back. The heat pipe was manufactured from 6061-T6 billet Al in accordance with industry specifications. The pipe was secured to the plate with M4 bolts and a representative adhesive, also in accordance with these specifications, to ensure an accurately representative configuration. The M4 bolts were tightened to a torque value of approximately 2.3Nm. The particular grade of Al was chosen as it was more readily available than the 6063-T6 and 7020-T6/2024-T6 grades of Al used for the actual heat pipes and panels respectively, and had similar yield properties. The target configuration is shown in Fig. 7.

Figure 7. Rear surface of Al6061-T6 fitted with representative heat pipe manufactured to industry specifications (left). Result of impact with blunt projectile (hex) at 66m/s into 2mm Al6061-T6 plate fitted with a representative heat pipe showing complete separation of heat pipe. Impact was along centre-line of pipe (right).

A series of three tests were conducted. These involved impacting the target panel with different tips as well as at different velocities and alignments. The primary purpose of this series of tests was to determine the effect that an obstruction such as a heat pipe would have on the harpoon's ability to penetrate the target panel. The results of this series of tests are detailed in table 3.

Table 3: Results from impact of harpoon into 2mm Al6061-T6 panel fitted with representative heat pipe

Test	Impact Velocity (m/s)	Tip	Impact Location	Result
1	65.85	Blunt (Hex)	Heat pipe centreline	Complete separation of heat pipe due to shear of flanges at mounting bolts.
2	49.97	Cone	Left of centre	Partial separation of heat pipe due to shear of left flange at mounting bolt. Harpoon remained attached to panel post penetration.
3	42.18	Integrated toggle	Heat pipe centreline	Partial penetration of panel and separation of heat pipe at bolt location closest to point of impact.

From these results it can be seen that a heat pipe does not prevent the harpoon from successfully penetrating a target panel. In all cases, the common failure mode was shear through the pipe flange at the mounting bolt(s) resulting in separation of the pipe from the target panel. High speed footage of test 1 showed bending of the pipe with initial harpoon penetration followed by clear separation from the panel. As a result of penetrating the panel at different locations with respect to the pipe centre line it could be seen that this separation occurred whether the harpoon impacted directly along the centre line of the pipe or along its edge. This is of significant benefit for an actual mission scenario where the precise locations of heat pipes, as well as harpoon impact location, may be unknown. In addition, the results of test 3 showed that even if the projectile impact energy is too low for full penetration of the target panel, the pipe will still separate. From these tests it can therefore be concluded that the flange is the weakest point for this target configuration and will reliably fail on impact, allowing successful harpoon penetration.

E. Oblique Impact Testing

In regards to impact angle, although normal impact and perforation of thin and moderately thick plates has been extensively investigated both analytically and experimentally by authors such as Goldsmith, Backman, Gupta, and Finnegan, data related to oblique impacts are not readily available. Oblique impact needs to be considered for an ADR harpoon system due to the possibility that the target may be spinning and even tumbling. The limited existing research shows that the ballistic limit for a given projectile changes with varying degrees of obliquity (Backman & Goldsmith, 1978). This is largely a result of increasing path length with increased obliquity as well as increased bending stresses due to the asymmetry of the loading (Zukas, 1982).

In order to determine the effect of obliquity on harpoon penetration, a series of preliminary tests were conducted with conical and blunt tips. These experiments were conducted at an angle of obliquity up to 40° by angling the target box. As the angles were determined with a standard protractor, a conservative uncertainty margin of +/-1.0° has been included. Testing was concluded at 40° due to damage which was incurred to the harpoon as a result of the projectile sliding along the face of the target plate and impacting the target holders. The results of the empirical tests are detailed in Table 3.

Table 3: Results of Oblique Impact Testing for 3mm Al5005H34 Target Plate

Tip Shape	Angle of obliquity +/-1.0°	Impact velocity (m/s)	Result
Cone (16mm, 24°)	20	43.5	Through
	30	44.3	Through
	40	44.3	Ricochet
	40	46.6	Embedded in target
	40	48.2	Through
Cube (16mm side length)	20	43.5	Through
	30	43	Through
	40	48	Skidded along target face

From these preliminary results it can be seen that the blunt tip appears to require a greater relative increase in energy in order to penetrate targets at increasing angles of obliquity. This can be concluded from the fact that, although it had a greater relative increase in energy between 30° and 40° in comparison to the conical tip, it failed to even embed in the target. These limited results were supplemented with simulation. These results are discussed in section G.

F. Effectiveness of Harpoon Lock-on Mechanisms

In order to allow de-orbiting of the debris, an effective lock-on mechanism needs to be developed. Preliminary studies already completed by Airbus Defence & Space have identified a number of options for this purpose including iterations of fixed and deployable barbs. Due to the increase in impact energy required for devices with fixed barbs, as well as a higher likelihood of debris creation, this project focused on testing two different deployable toggle mechanisms. The first used a simple spring activated toggle mechanism, whilst the second was an integrated tip/toggle design (Fig. 8). The second mechanism deployed under the influence of gravity during testing. As such, it would require a simple strain-energy device, such as a tape spring, to facilitate deployment in zero-g. This tip was designed to improve reliability in impacts where the target panel may be obstructed by heat pipes or obstructions. In both cases, premature deployment of the toggle mechanisms was prevented by fitting collars which were forced to release upon impact with the target panel. Both toggle mechanisms were tested during impact with 23mm thick Al H/C panels with 1mm Al face sheets. As shown in Fig. 8, both mechanisms operated reliably and effectively.

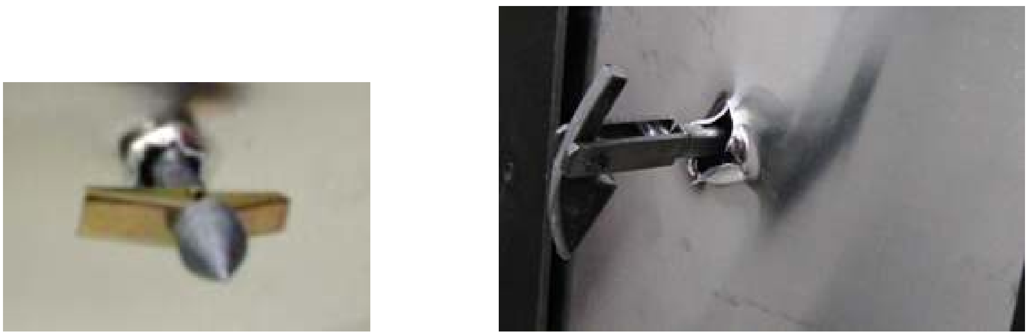

Figure 8. Harpoon with spring activated toggle (left) and integrated toggle (right) in deployed configurations.

In addition to testing the deployment of these mechanisms, their ability to withstand the expected forces associated with de-orbiting manoeuvres was also established. A study conducted by Airbus Defence & Space suggests that an average force of approximately 500N, with a peak as high as 2-3kN in the event of a high thrust

de-orbit manoeuvre, could be experienced. This testing was conducted on Al H/C panels. These samples were chosen instead of Al plate as they have a lower resistance to shear and therefore represent the worst case scenario. They are also typical of spacecraft structures. Of note, the CFRP panel also used in satellite applications was not available for testing. The testing involved clamping the target panel with embedded harpoon in a tensile testing machine and recording the peak force achieved before failure of either the mechanism or target material. The results of the testing are detailed in Fig. 9.

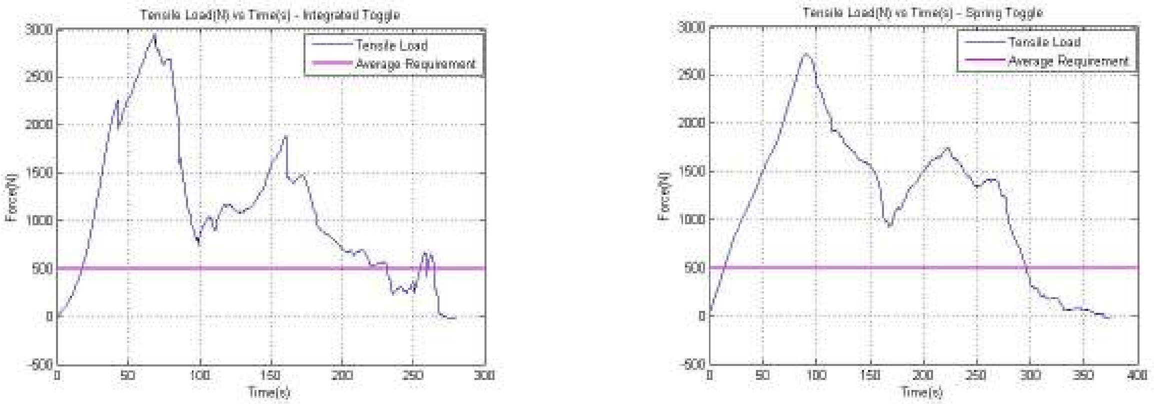

Figure 9. Pull-out resistance of integrated toggle locked onto Al H/C panel (left), and pull-out resistance of spring activated toggle locked onto Al H/C panel (right).

As a result of conducting this test it was found that the peak load experienced by the integrated toggle was 2,950N, while the spring activated toggle experienced a peak load of 2,720N. As a result, both were capable of withstanding the minimum load requirement of 500N. Pull out occurred during the spring toggle test as a result of the failure of the toggle. The test of the integrated toggle resulted in failure of the honeycomb panel with the toggle remaining entirely undamaged. This suggests that the integrated toggle would be capable of withstanding much higher tensile forces and is better suited to applications where high peak forces are likely. This enhanced capability is due to its more robust design and larger surface area over which the tensile force can act. In addition, although the integrated toggle closed up as the honeycomb failed, it was noted that it was still capable of supporting the minimum load requirement of 500N in a partially deployed configuration. This suggests that this type of toggle can be relied upon to provide sufficient lock-on to the target even if it does not fully deploy on impact.

G. Impact simulation using ANSYS/Autodyn

Part of this study involved numerical modeling to simulate impact into Al and CFRP targets. The reasons for conducting simulation were: to identify the suitability of using simulation as a harpoon development tool; to obtain further results for the study into oblique impact; to parameterise tip dimensions and therefore reduce the amount of experimental testing required; and to simulate impact into CFRP targets. In regards to the models simulating impact into Al targets, a linear equation of state was used. This was chosen due to the fact that the relatively low velocity of the impacts being simulated meant that only the initial (linear) portion of the associated material Hugoniot was relevant. The strength model chosen was the Johnson-Cook model, whilst the failure model was based on effective plastic strain. The Johnson-Cook strength model was chosen as it incorporates a strain hardening component which is an important consideration for low velocity impact into Al targets. The model also includes strain rate and thermal softening effects. The results of quasi-static testing of 3mm Al5005H34 samples were used to determine the primary constants required for the Johnson-Cook strength model. Extensive convergence testing was also conducted to improve the accuracy of the simulations. This involved mesh refinement, adjustments of hourglass damping controls, determining the sensitivity of results to variations in the Johnson-Cook parameters, and optimising target panel size to minimise edge effects whilst maintaining realistic computation times. In addition, the hourglass energy was monitored and maintained at below 10% for the majority of the simulations and the energy error was maintained below 5%.[3]

In order to assess the suitability of using simulation to support the harpoon development process, ballistic limit simulations were run and convergence with empirical results tested. This showed that varying degrees of agreement existed between experimental and simulated ballistic limits. Whilst the simulated ballistic limit for the conical tip exactly matched that obtained experimentally, the model over-predicted the ballistic limit for the

[3] Hourglass energy is defined on the LS-Dyna Support site, http://www.dynasupport.com/howtos/element/hourglass, as '....nonphysical, zero-energy modes of deformation that produce zero strain and no stress.' They therefore need to be minimised in simulations as they can result in unphysical results.

blunt projectiles. The relationship between circumference and ballistic limit identified experimentally however was confirmed with simulation. In addition, the petaling and plugging failure modes shown by the simulations were representative of those achieved experimentally.

In regards to oblique impact simulations, these confirmed that a blunt tip requires more energy to perforate a 3mm Al plate at high angles of obliquity in comparison to a conical tip, particularly at angles in excess of 45°. Custom tips were also designed and tested for their performance at increasing angles of obliquity however, their performance was worse than that achieved by a conical tip shape. Simulations involving the parameterisation of conical tips were also run where the tip diameter was varied between 16-20mm. This showed that the ballistic limit increases with tip diameter.

In regards to harpoon impact into CFRP, this simulation used an SPH solver in Autodyn-2D. This solver was chosen due to its meshless nature and therefore greater applicability to impact simulations of brittle materials in comparison to the Lagrange solver. A data set developed in a previous study on testing, material modeling, and numerical simulation of impact on CFRP was used in this solver (Wickleim et al., 2008). Simulations of impact into 1mm CFRP panel by both blunt and conical projectiles at their ballistic limits of 11m/s and 35m/s respectively, detailed in Fig. 10, showed significant differences in debris formation, debris velocity, and projectile deceleration. Specifically, the debris formed during impact by a blunt projectile is more coherent and has a lower velocity than that produced by a conical tip. The maximum velocity of these debris particles is approximately 40m/s whilst debris created by a conical projectile reaches approximately 590m/s. The significant difference in ballistic limits can be explained by the fact that CFRP has low impact strength but high tensile yield strength (Greszczuk et al., 1975). As penetration by the conical tip results in piercing and therefore a high tensile load, it experiences greater deceleration than the blunt tip which causes the CFRP to fail as a result of high impact-loading. It is also worth noting that debris formation is initiated on the back-face of the target. This is typical of impact damage incurred by thin composite targets (Zukas, 1982) and means that any debris created by the harpoon will remain internal to the target.

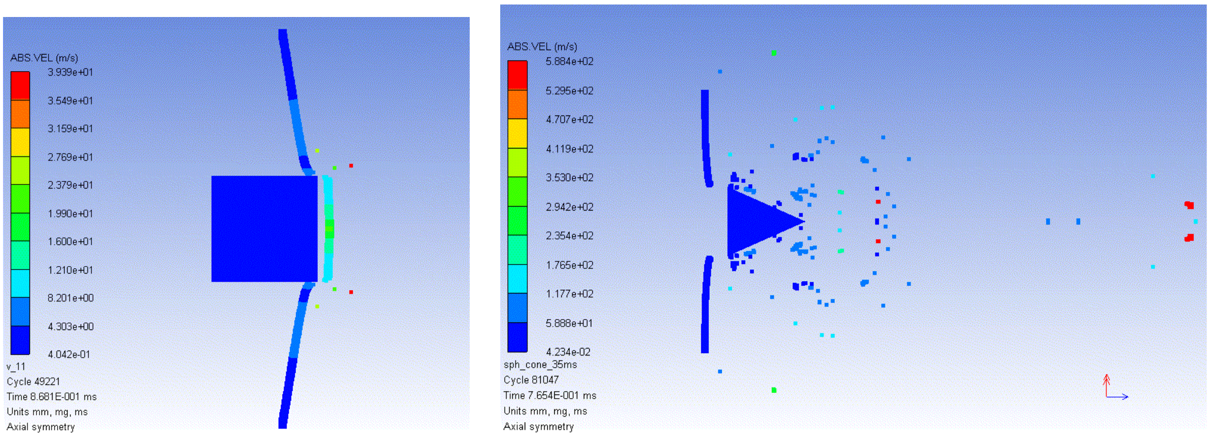

Figure 10. Simulation of blunt projectile impacting 1mm CFRP at ballistic limit (11m/s) (left), and simulation of conical projectile impacting 1mm CFRP at ballistic limit (35m/s) (right).

IV. Conclusions

In this paper the results of a study to determine the effectiveness of a harpoon as an ADR system were presented. These results are summarised in table 4.

Table 4. Results of study into the use of a harpoon in an ADR application

Outcome	Result	Implication
III (A)	The ballistic limit for penetration is less for a blunt nosed projectile than a conical one, however, this only applies to normal impact. The conical tip requires a less significant increase in energy for oblique impacts.	A conical tip would be more versatile in an ADR mission as targets are likely to be rotating or tumbling therefore resulting in an oblique impact.
III (B)	Secondary debris is created by both blunt and conical projectiles. Blunt projectiles create a plug, while conical projectiles can create minor fragmentation and spalling. Secondary debris for both cases is on the side opposite to impact.	Neither blunt nor conical tips prevent secondary debris formation, therefore, this criteria should not be used in the selection of tip shape.
III (C)	Penetration of 3mm Al plate targets at low temperatures reduces secondary debris.[4] This results from increased brittleness of the target material and therefore a reduction in ductile spalling. The energy required to penetrate a low temperature Al target is also increased.	Targets in eclipse may be successfully penetrated with an increase in impact energy and a reduction in the likelihood of secondary debris formation, if a conical tip is used.
III (D)	A harpoon can successfully penetrate Al targets, including those with heat pipe obstructions with the creation of internal debris only.	A harpoon can successfully penetrate a target panel with heat pipe obstructions. This applies whether the impact site coincides with the heat pipe centreline or is partially offset.
III (E)	A conical projectile was shown to be capable of penetrating a 3mm Al target up to an angle of obliquity of 40°.	A harpoon with a conical tip can penetrate targets that are rotating or tumbling where the resulting impact angle is 40° or less.
III (F)	Results of toggle testing showed that the harpoon could successfully lock onto an Al target panel and withstand the forces expected during de-orbiting manoeuvres.	Current toggle designs are sufficient to facilitate de-orbiting of Al H/C and Al panel targets.
III (F)	An integrated toggle design was proven to be more robust than a spring loaded toggle.	An integrated toggle may provide a more reliable solution than a spring toggle for actual mission scenarios.
III (G)	Simulation undertaken with ANSYS/Autodyn showed that numerical modeling can be used as an effective tool to predict failure modes, likely debris creation for both Al plate and CFRP, and relative (but not absolute) impact speeds required for different tip shapes during normal and oblique impacts.	Simulation can be used to reduce the quantity of experimental testing required for further harpoon characterisation studies, such as oblique impact modeling.
III (G)	Numerical modeling shows that the ballistic limit of a conical projectile is proportional to its base diameter.	Reducing the base diameter of conical tips reduces required impact energy and therefore the risk of secondary debris creation. Propellant requirements will also decrease.

[4] This applies to the 5005H34 grade of Al used in this study. The applicability to other grades of Al will be verified in further work.

From these results it can be concluded that a harpoon represents a viable option as an ADR system.

V. Further Work

Additional parametric studies are proposed to further validate the use of a harpoon in an ADR application. These include additional empirical and simulation studies of oblique impacts, testing toggle deployment during impact with obstructed and oblique panels, and conducting a comparison between Al5005H34 and higher strength Al to allow extrapolation of the results to satellite structures made with different Al alloys. Tip optimisation which develops on the investigation of ballistic limit and tip shape should also be undertaken. In addition, the design and testing of an effective damper system is required. Such a damper will prevent the harpoon from passing through a target panel due to excess impact energy. Finally, a preliminary study of tether deployment is proposed to improve confidence in the ability of the tether to unravel freely during firing of the harpoon. These final two aspects will be covered as part of the final report for this thesis, however, were omitted from this summary due to length restrictions.

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