Lightweight Bulldozer Attachment for Construction and Excavation on the Lunar Surface

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A lightweight bulldozer blade prototype has been designed and built to be used as an excavation implement in conjunction with the NASA Chariot lunar mobility platform prototype. The combined system was then used in a variety of field tests in order to characterize structural loads, excavation performance and learn about the operational behavior of lunar excavation in geotechnical lunar simulants. The purpose of this effort was to evaluate the feasibility of lunar excavation for site preparation at a planned NASA lunar outpost. Once the feasibility has been determined then the technology will become available as a candidate element in the NASA Lunar Surface Systems Architecture. In addition to NASA experimental testing of the LANCE blade, NASA engineers completed analytical work on the expected draft forces using classical soil mechanics methods. The Colorado School of Mines (CSM) team utilized finite element analysis (FEA) to study the interaction between the cutting edge of the LANCE blade and the surface of soil. FEA was also used to examine various load cases and their effect on the lightweight structure of the LANCE blade. Overall it has been determined that a lunar bulldozer blade is a viable technology for lunar outpost site preparation, but further work is required to characterize the behavior in 1/6th G and actual lunar regolith in a vacuum lunar environment.

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Nomenclature

w	=	blade width
l_s	=	blade length
l	=	blade height
d	=	vertical cut depth
β	=	rake angle
δ	=	external friction angle
g	=	gravitational constant
γ	=	material density
c	=	cohesion
ϕ	=	internal friction angle
q	=	surcharge mass
e_b	=	blunt edge thickness
α_b	=	blunt edge angle
s	=	side plate thickness
v	=	vehicle velocity
r	=	blade radius
h	=	soil prism height

I. Background – Why is Lunar Excavation Useful?

AMONG the numerous operational and technical challenges of establishing a lunar outpost is the development of construction and excavation technologies. With the exception of Apollo 12, all of the Apollo landers touched down in an empty landscape devoid of space hardware. Apollo 12 landed 180 meters away from the Surveyor III lander and its engine exhaust ejected regolith off the surface, effectively sandblasting the nearby Surveyor III. Multiple landings at a lunar outpost will eject the loosely packed top levels of regolith at the outpost hardware. One method of mitigation is the construction of landing pads and protective berms. It is proposed that landing pads can be constructed by excavating to the densely compacted regolith 30 cm below the surface and using lunar regolith to build berms as blast barriers to surround the excavated area.

The NASA Lunar Architecture Team (LAT) proposed an architecture in 2006 to establish a lunar outpost that includes in-situ resource utilization (ISRU). The architecture is planned to be implemented in a series of missions to establish a lunar outpost that begin in 2019 and continue at 6 month intervals into 2027 (Cook[7]). By 2023, the outpost might be configured as shown in Fig. 1 (Mueller and King[8]). This architecture is just one example of many architecture scenarios being studied by NASA and all data is representative only and not definitive.

In addition to building landing pads and blast protection berms, lunar regolith excavation is also useful for a variety of other civil engineering and construction type of tasks which are listed in table 1 below.

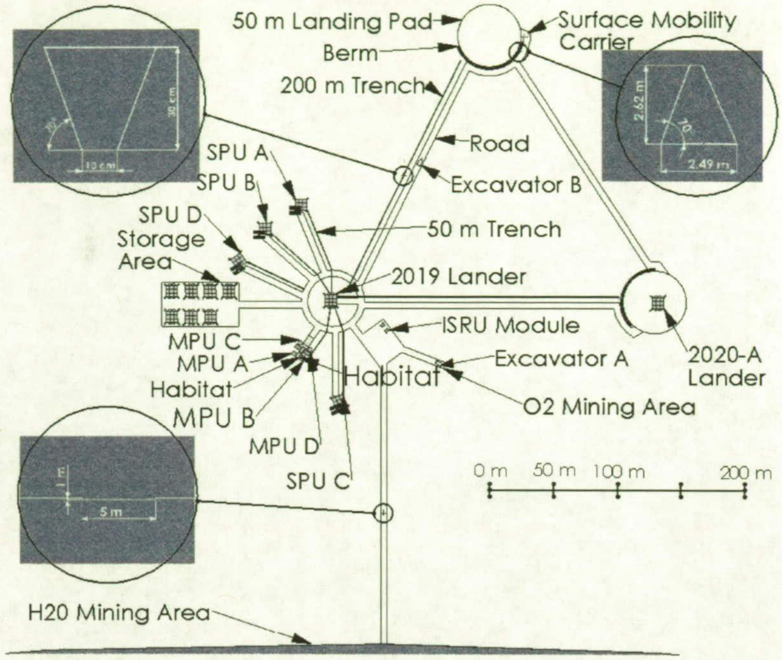

Figure-1. Example 2023-B Typical Lunar Outpost Site Plan

Outpost development requires excavation for landing and launch sites, roads, trenches, foundations, radiation and thermal shielding, etc; furthermore, ISRU requires excavation as feedstock for water processing and oxygen production plants. Several alternative scenarios are under consideration at NASA that include either carbothermal or hydrogen reduction process to extract Oxygen from regolith and using special materials to avoid covering habitat modules. Table 1 presents the mass of excavated regolith required by task for each mission for the Hydrogen reduction processing and habitat structures shielded by regolith (H2 Reduction O2/Hab Shield) alternative.

	2019	2020a	2020b	2021a	2021b	2022a	2022b	2023a	2023b
Cable Trenches	37,644	56,465	0	9,411	0	9,411	0	0	0
Roads	150,000	150,000	112,500	37,500	0	37,500	37,500	0	0
Landing Pad	588,750	588,750	0	0	0	0	0	0	0
Berms	282,726	282,726	0	0	0	0	0	0	0
Foundations	0	1,200	4,500	1,200	2,250	600	4,200	1,350	0
Hab/Shield Trench	0	0	357,668	0	178,834	0	178,834	0	0
Hab/Shield Roof	0	0	0	66,880	66,880	66,880	66,880	0	0
O2 ISRU	0	0	0	0	0	0	0	250,000	250,000
Ice ISRU	0	0	0	0	0	0	0	50,000	50,000
Total Regolith (MT)	1,059	1,079	475	115	248	114	287	251	250
Total Ice Regolith (MT)	0	0	0	0	0	0	0	50	50

Table 1: Excavation requirements (Kg) for a Representative Lunar Outpost Mission

To construct these surface features excavation devices similar to earth-moving equipment will be needed. Engineers at the Kennedy Space Center have developed the first prototype of a lunar excavation blade. The Lunar Attachment Node for Construction and Excavation (LANCE) blade attaches to the prototype lunar truck Chariot, built by the Johnson Space Center. The LANCE blade is a lightweight implement which, in combination with the Chariot platform, can perform lunar site preparation activities such as area clearing of rocks, leveling, dozing, grading, and berm construction. The blade is made from an aluminum support structure with a unique composite moldboard. The composite moldboard is constructed from alternating layers of carbon fiber and proprietary toughening polymer fibers in an epoxy resin matrix, with a polyurethane topcoat. The toughening polymer allows the composite to have an increased elastic deformation zone, similar to metals but with the decreased mass of a carbon fiber composite. Polyurethane on the outermost surface provides a tough wear resistant finish. The 4.1 meter long blade can be independently adjusted using an electromechanical actuator to actively set digging depth. The lightweight construction of the entire system amounts to a mass savings of over 70% compared to a similarly sized commercial dozer blade.

II. Methods of Plume Mitigation

Lander rocket engine plume interaction with the lunar regolith causes ejecta of the regolith particles at speeds of 1,000 m/s to 2,000 m/s according to research done by Metzger[10]. These particles are typically sized from 20 microns to 100 microns in diameter, but nevertheless can cause damage to emplaced lunar assets. Analysis of the Apollo landing plumes has established that the plume ejecta travels in a wide low swath that extends up to 3 degrees from the horizontal surface (Metzger[10]). Therefore, one method of plume mitigation is to erect a barrier at the perimeter of the landing area to block the path of these ejected particles. Since transported mass from the Earth is extremely expensive, it is more cost effective to use in-situ regolith to build a local barrier such as a regolith berm. There are other methods of plume mitigation as well, such as creating a hardened landing pad by sintering, polymer deposition or other methods, In addition the barrier could be made of non-lunar materials that have been brought or re-cycled. For the purposes of this paper, only in-situ regolith berms will be considered as a blast barrier.

III. Lunar Attachment Node for Construction & Excavation (LANCE)

A lunar bulldozer blade was developed in a custom design to interface and operate with the Chariot mobility platform also known as a “Lunar Truck”. The Chariot can use a variety of implements and the bulldozer blade known as Lunar Attachment Node for Construction & Excavation (LANCE) is one instance of such implements. The intended use of the LANCE blade is as a prototype “proof of concept” demonstration device for lunar site preparation. It is made of an aluminum frame with a composite carbon fiber /epoxy mold board.

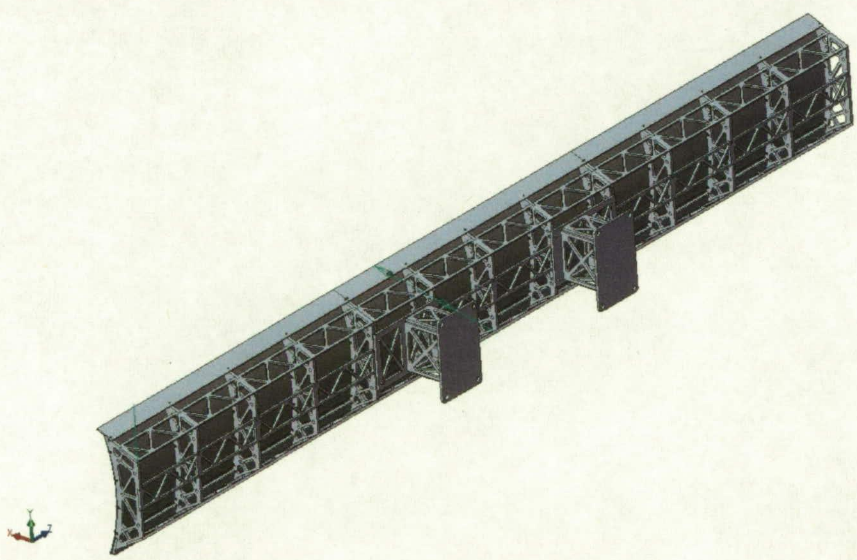

Figure 2 – LANCE Blade Isometric View

A. LANCE Configuration

The LANCE bulldozer blade was mounted onto the Chariot mobility platform via a structural interface consisting of five structural hard points that connected directly to the chrome-molybdenum Chariot steel frame. The blade was mounted in a static fashion, with future enhancements expected which will make give it a motion controlled vertical degree of freedom in order to vary the cut depth as desired. Another future enhancement that is expected is a quick attach mechanism which will allow rapid assembly to the Chariot. The blade was mounted as close as possible to the Chariot frame in order to reduce cantilever moment loads and deflections. The result is an extremely rigid assembly which provides superior control due to the close coupling of the chariot and blade structures. By avoiding a long cantilever arm, as is typical in commercial applications, several issues are eliminated such as wash-boarding of the excavation surface and other delayed control loop effects. Another important aspect of the blade design is the fact that it covers the port to starboard span of the rover wheels so that the bulldozed and graded surface provides a smooth path for the wheels to drive on, thereby enhancing control and allowing slot-dozing techniques to be used.

Figure 3 - LANCE Blade Grading a Simulated Landing Site in Moses Lake, Washington State, USA

B. Lightweight Blade Construction Techniques

Typically excavation tools are made with heavy welded steel construction. This type of construction is very efficient for a terrestrial application, but when designing for aerospace application the goal is typically to maintain strength and durability while minimizing weight. To achieve this goal the design team looked at many different construction techniques. For example, welded high strength steel with smaller wall thicknesses, welded aluminum, composites, and hybrid aluminum-composite structures. Mass trades were performed and the high strength steel and welded aluminum frames were comparable while the composite structure approximately weighed 2 times less. The high strength steel with smaller wall thicknesses presented difficult challenges during the manufacturing process specifically during welding. The composite structure was very promising but required complex finite element analysis and very specific manufacturing processes. The welded aluminum frame requires special weld techniques due to the fact that aluminum anneals around the weld affected areas. The annealed aluminum can have up to 70% loss in material strength when compared to a heat treated aluminum stock. Two techniques were considered for avoiding this loss in material strength, removing the load paths from the weld affected areas and post-weld heat treatment. Removing the load paths from the weld affected areas generally meant adding more material and was found to be not optimized for light weight design. The post-weld heat treatment required certain alloys of aluminum stock. Aluminum 6061is typically used for post-weld heat treatment, while also being readily available and easy to machine and weld. Post-weld heat treatment was found to increase the annealed aluminum's material strength to within 85% of 6061-T6 material strength[6]. After considering the required manufacturing processes for the high strength steel, welded aluminum, and composite structure the welded aluminum frame using post weld heat treatment was selected. The hybrid aluminum composite frame was reinforced by making the front moldboard of the frame out of carbon fiber epoxy, but the majority of the load bearing frame was made from the post-weld heat treated frame. The hybrid design presented less initial risk then the complete composite structure but still allowed for more weight savings while pushing the limits of typical excavation tools.

The blade is several meters long to ensure that the LER's wheels are covered during grading to cover the wheel tracks. The structure consists of vertical ribs along the length of the blade with horizontal stiffeners connecting the ribs together (Figure 4). The ribs and horizontal stiffeners fit together like a jig helping to keep the frame straight during welding (Figure 5). The blade was separated into three 2 meter sections to make manufacturing and heat treatment easier. The composite moldboard is made from 0 degree and +-45 degree layers of carbon fiber with a toughing polymer fiber in between each layer of carbon fiber. This polymer fiber helps dampen the loads from grading by distributing the loads across the moldboard. The front of the moldboard is coated with a thin layer of urethane much like truck bed liner. This urethane layer protects against abrasion from the soil during grading. The assumption is that the urethane coating helps absorb the impacts from the soil effectively creating an abrasive boundary layer. The carbon fiber moldboard is bolted to the front of the aluminum structure using the ribs (Figure 6).

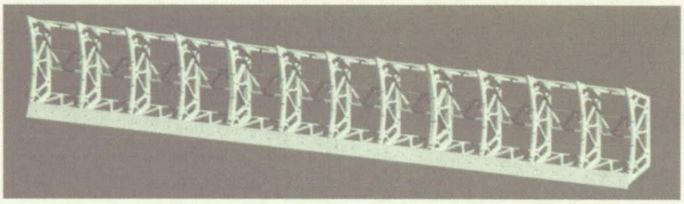

Figure 4: Rib and horizontal stiffener construction

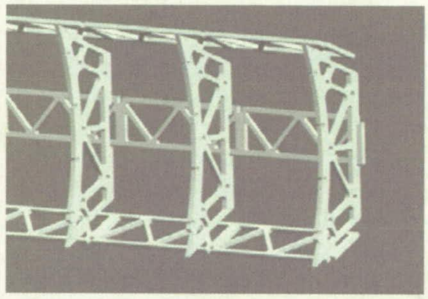

Figure-5: Jig Construction

The cutting edge is bolted on and made from hardened steel (Figure 6). During grading operations forward grading was found to be effective during initial leveling operations, but for final grading a back drag operation creates a very smooth surface. Opposite the cutting edge a hardened plate was bolted on to protect during the back drag operations (Figure 6). The aluminum frame is bolted onto an aluminum plate which serves as a mounting plate to the back of the rover (Figure 6).

Figure 6: Lance blade diagram mounted on Chariot

C. Instrumentation

The LANCE blade was outfitted with instrumentation to aid in the development of software models for lunar system design. These models include modules that resolve the excavation forces from activities such as dozing into mass and power estimates for given system designs. In order to validate these models the LANCE blade was used in soil tests at Johnson Space Center. During these tests the LANCE blade was attached to the Chariot vehicle and driven through a prepared simulant bed at various depths and velocities. To record the load on the system from the excavation forces the blade was equipped with five load button style load cells. The load cells were sandwiched between the LANCE interface plate and its five attachment points. Laser distance meters were used to record the depth of the blade and were attached to outrigger mounts on each end of the LANCE blade pointing downward toward the simulant bed. Another laser distance meter was positioned above the blade and pointing outward toward a stationary target. This meter was used to record the velocity of the blade.

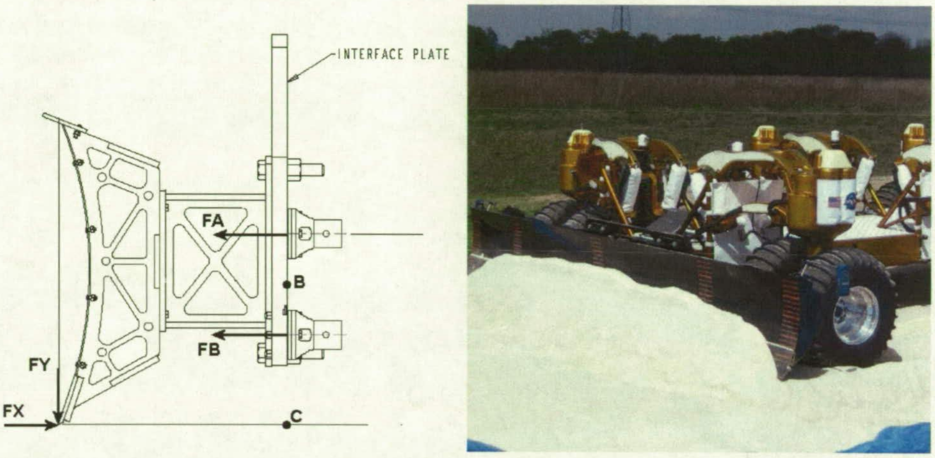

Figure 7 - Side View (inches) with Load Cells at FA and FB (left) and the Blade pushing GRC-1 Lunar Regolith Simulant During a Test (right)

The load cells were recorded using a National Instruments field point data acquisition (DAQ) system. The DAQ acquired and scaled the resistive measurement from the load cells and passed it over an ethernet connection on-board Chariot to a laptop running a Lab View VI for data logging. The VI on the laptop was also connected to the laser distance meters via a Bluetooth connection. All of the measurements; depth, velocity, and force were recorded versus elapsed time. Also, in an effort to record the surcharge in front of the blade, horizontal stripes were placed at regular intervals on the surface of the LANCE moldboard. Video cameras were synchronized with the VI and provided views of the surcharge during the test from a head-on and side view.

IV. ANALYSIS

A. Prediction of Excavation Forces by Classical Soil Mechanics Methods

Gallo and Wilkinson[9], reported that;" An Excavation System Model has been written to simulate the collection and transportation of regolith on the moon. The calculations in this model include an estimation of the forces on the digging tool as a result of excavation into the regolith. Verification testing has been performed and the forces recorded from this testing were compared to the calculated theoretical data. This is the initial correlation of actual field test data to the blade forces calculated by the Excavation System Model and the test data followed similar trends with the predicted forces. The Johnson Space Center (JSC) has built a prototype lunar vehicle that was tested with a bulldozer type blade attached to the front. The bulldozer blade was developed at the Kennedy Space Center (KSC). This testing occurred in soil designated as GRC-1 which is a mixture of different types of sand. The GRC-1 soil was developed at the Glenn Research Center (GRC). The properties of the sand were known as well as the geometry of the vehicle and digging tool.

The analysis predicted blade forces using the Balovnev equations[4]. Two separate equations were used to predict the blade forces. One was derived for a bucket and the other for a blade. Both were coded to compare the two different theoretical methods to the data. The test data was obtained for a wide bulldozer blade but the Balovnev blade equations did not necessarily result in the best correlation with the data.

1) Balovnev Bucket Force Equations

Horizontal Blade Force =

$wd\, A_1\, (1 + \cot\beta \tan\delta)\, [dg\gamma/2 + c \cot\phi + gq + \text{BURIED} * (d - l \sin\beta)\, g\gamma\, (1\text{-}\sin\phi)/(1+\sin\phi)] +$

$we_b\, A_2\, (1 + \tan\delta \cot\alpha_b)\, (e_b g\gamma/2 + c \cot\phi + gq + dg\gamma\, (1\text{-}\sin\phi)/(1+\sin\phi)) +$

$d\, A_3\, (2s + 4l_s \tan\delta)\, [dg\gamma/2 + c \cot\phi + gq + \text{BURIED} * (d - l_s \sin\beta)\, g\gamma\, (1\text{-}\sin\phi)/(1+\sin\phi)]$ (3)

where BURIED = 1 if entire bucket is below the soil otherwise BURIED = 0

$A_1 = A(\beta)$

$A_2 = A(\alpha_b)$

$A_3 = A(\pi/2)$

Replace '**x**' in the following equations with β for A_1, α_b for A_2 or $\pi/2$ for A_3

if $\mathbf{x}$ [$0.5\, [\sin^{-1}(\sin\delta/\sin\phi) - \delta]$

$A(\mathbf{x}) = (1 - \sin\phi \cos 2\mathbf{x})/(1 - \sin\phi)$

if $\mathbf{x} > 0.5\, [\sin^{-1}(\sin\delta/\sin\phi) - \delta]$

$A(\mathbf{x}) = [\cos\delta\, (\cos\delta + (\sin^2\phi - \sin^2\delta)^{1/2})/(1 - \sin\phi)]\, \exp[(2\mathbf{x} - \pi + \delta + \sin^{-1}(\sin\delta/\sin\phi)) \tan\phi]$

Vertical Blade Force = Horizontal Blade Force * $\cos(\beta + \delta) / \sin(\beta + \delta)$ (4)

2) Balovnev Blade Force Equations

If $(\beta <= (0.5 \sin^{-1}(\sin\delta/\sin\phi) - \delta/2))$

$A1 = (1 - \sin\phi \cos(2\beta)) / (1 - \sin\phi)$

If $(\beta > (0.5 \sin^{-1}(\sin\delta/\sin\phi) - \delta/2))$

$A1 = (\cos\delta\, (\cos\delta + (\sin^2\phi - \sin^2\delta)^{0.5})) / (1 - \sin\phi)\, \text{Exp}((2\beta - \pi + \delta + \sin^{-1}(\sin\delta/\sin\phi)) \tan\phi)$

$A2 = 0.8\, g\gamma w\, (\tan\delta + \tan\phi) \cos^2\phi$

$A3 = \sin^{-1}(1/(2r/h))$

$A4 = A2\, rh / (2\tan\delta)$

$A5 = A2 \cos(A3)\, r^2 / (1 + \tan^2\delta)$

$A6 = A2 \sin(A3)\, r^2 \tan\delta / (1 + \tan^2\delta)$

$A7 = \text{Exp}(2A3 \tan\delta)$

$A8 = (A4 + A5)(A7 - 1) - A6\, (A7 + 1)$

$B1 = A1\, wg\gamma d^2 \sin(\beta+\delta) / \sin\beta / \cos\delta / 2$

$B2 = A1\, dwc \sin(\beta+\delta) / \sin\beta / \cos\delta / \tan(\phi)$

$B3 = A1\, A8 \sin(\beta+\delta) / \cos\delta / ((\tan\beta + \text{Tan}(\pi/4 - \phi/2)) / (\tan\beta\, \text{Tan}(\pi/4 - \phi/2)))$

$B4 = A1\, 0.8\, g\gamma dwh \sin(\beta+\delta) / \sin\beta / \cos\delta$

$B5 = 0.8\, g\gamma wh^2 \cos^2\phi / 2$

Horizontal Blade Force = B1 + B2 + B3 + B4 + B5 (5)

3) Luth-Wismer Blade Force Equations

A third set of equations was used to predict the forces on the blade to provide an additional comparison to the measured forces. This third set is designated as the Luth-Wismer equations[5]. The Luth-Wismer equations predict a blade force higher than the Balovnev blade equations when compared to the measured value. As before, the vertical force, FY is small because of the high rake angle. The horizontal force, FX calculated by Luth-Wismer is roughly 10 times the force from the experimental data. Unlike the Balovnev equations, the force calculated from Luth-Wismer is a function of vehicle velocity whereas velocity is not a variable in Balovnev.

$$\text{Horizontal Blade Force} = \gamma\, g\, w\, d^{1/2}\, l^{1.5}\, \beta^{1.73}\, (d / (l \sin\beta))^{0.77}\, (1.05\, (d / w)^{1.1} + 1.26\, v^2 / g / l + 3.91) \quad (6)$$

DESCRIPTION	VARIABLE	UNITS
blade width	w	meter
blade length	l_s	meter
blade height	l	meter
vertical cut depth	d	meter
rake angle	β	degrees
external friction angle	δ	degrees
gravitational constant	g	meter/second^2
soil density	γ	kilogram/meter^3
cohesion	c	Newton / meter^2
internal friction angle	ϕ	degrees
surcharge mass	q	kilogram/meter^2
blunt edge thickness	e_b	meter
blunt edge angle	α_b	degrees
side plate thickness	s	meter
vehicle velocity	v	meter/second
blade radius	r	meter
soil prism height	h	meter

Table 2 - Input Data to Blade Force Equations

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Although the Balovnev bucket force equations performed the best compared to the data obtained, there were too many un-controlled circumstances in the GRC-1 simulant test since it was performed outdoors in Houston, Texas and without the instrumentation desired which would be typical of a laboratory soil bin facility. In addition, the quality and simulant fidelity of the GRC-1 is questionable. Therefore further testing was desired with a higher fidelity simulant. GRC-3 is a higher fidelity simulant (sand with river silt mix) developed at the Glenn Research Center which, when prepared correctly, attempts to mimic the cohesion of lunar regolith on the moon. A further round of testing was performed at Johnson Space Center in November 2008 with GRC-3 in order to attempt to verify the predicted values from the classical methods presented here. These results will be the subject of a future paper. Overall, it was concluded that the prediction capability of the Balovnev bucket equations was promising but not accurate enough to use for design load cases, so further work is required. Subsequently, empirical test values from Chariot draw bar pull were used to generate load cases for the LANCE blade design.

B. Finite Element Analysis

LANCE structural stresses were modeled using the COSMOSWorks finite element analysis software. The Pathfinder blade is constructed primarily of machined aluminum parts that are welded together. In order to estimate the stresses that the Pathfinder blade experienced during usage analyses were performed in two scenarios. The first examined a worst-case scenario by applying a 5000-lbf load to the outside of the blade to simulate the condition where the blade contacts a large rock on the lower corner. This is an appropriate scenario to analyze as there could be large rocks buried in the lunar soil. NASA reported approximately 5000 lbf pushing (draw bar) force at Chariot wheel slip on a firm surface. The second scenario used forces measured during a series of experimental tests performed by NASA to model stresses in the blade.

In addition to experimental testing of the LANCE blade with GRC, engineers at the Colorado School of Mines (CSM) completed analytical work on the expected draft forces and structural analysis. The CSM team utilized finite element anaylsis (FEA) to study the interaction between the cutting edge of the LANCE blade and the surface of soil. FEA was also used to examine various load cases and their effect on the lightweight structure of the LANCE blade. The current analytical models do not allow for a time varying accumulation of soil in front of the blade, nor can they calculate the force distribution over the surface of the blade. Finite element analysis (FEA) methods can help analyze the horizontal force increase with forward motion over time while varying the surcharge from zero to the maximum steady state surcharge. 3D Finite element analysis will also allow for a stress/force distribution to be calculated on the blade at any time during the simulation. The total horizontal force on the blade, calculated with FEA, could then be compared to the analytical models and the experimental data. FEA also allows for a more accurate constitutive soil model which describes the soil behavior in much more accurate detail than assumed in the analytical models. FEA will thus allow a more accurate prediction of the expected excavation forces which will result in the lightest weight, most reliable blade design.

1) Stress Equations and Formulas

For the maximum stress calculations the von Mises stresses criterion was used. The von Mises stress equation takes into account stresses in all locations to calculate a combined stress. The equation for von Misses stress is:

$$\sigma_{vm} = \sqrt{\frac{(\sigma_x - \sigma_y)^2 + (\sigma_x - \sigma_z)^2 + (\sigma_y - \sigma_z)^2 + 6(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2)}{2}}$$

σ_{vm} = von Mises stress

σ_x = stress in x direction

σ_y = stress in y direction

σ_z = stress in z direction

τ_{xy} = shear stress in xy direction

τ_{xz} = shear stress in xz direction

τ_{yz} = shear stress in yz direction

The reported displacement is the URES value. The URES displacement is the displacement between an unloaded and loaded model. The equation for the URES displacement is:

$$URES = \sqrt{\delta_x^2 + \delta_y^2 + \delta_z^2}$$

δ_x = displacement in x direction

δ_y = displacement in y direction

δ_z = displacement in z direction

The reported factor of safety values are based on the yield strength of the material and the stress at the location. The factor of safety equation is:

$$FOS = \frac{s_y}{\sigma_{vm}}$$

s_y = yield strength

σ_{vm} = von Mises stress

2) Model Creation

The first step in analyzing the Pathfinder blade was to convert all the parts from a Pro-E Computer Aided Design (CAD) commercial software format to a SolidWorks CAD software format. Then the parts were assembled into three different SolidWorks models: the full blade, two-thirds of the blade, and half of the blade. The purpose of the three models was to reduce analysis time by taking advantage of symmetrical loading conditions to use smaller models when possible. The full blade model shown in Figure 8 analyzed non-symmetric loads

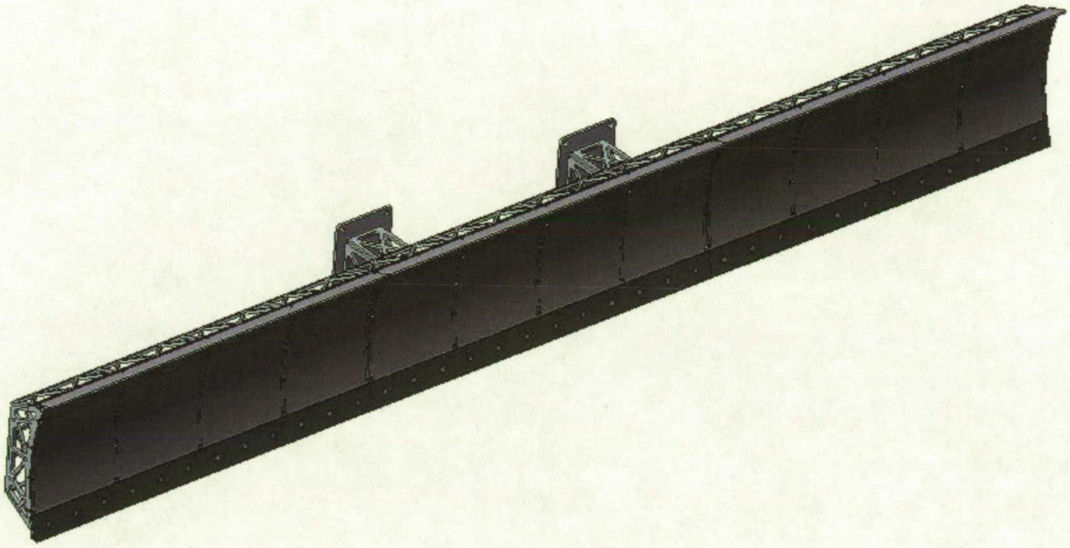

Fig. 8 - Full blade model front

3) Initial Analyses

The yield strength for the welded parts was multiplied by 0.85 in case welding reduced the strength at the welds. In this analysis case the mold board was assumed to be made of aluminum. A 5000-pound force was applied at the location shown by the pink arrow in Figure 9. The mounting brackets were fixed at the location where they attached to the Chariot frame. The locations of the restraints are shown by the green arrows and faces in Figure 9. The initial analyses used bonded contacts. The highest stress in the bonded model from the 5000-pound force occurred in the horizontal support. Several other cases were run and the COSMOS-Works Commercial software FEA model was subsequently further optimized to help in the design process of the LANCE blade.

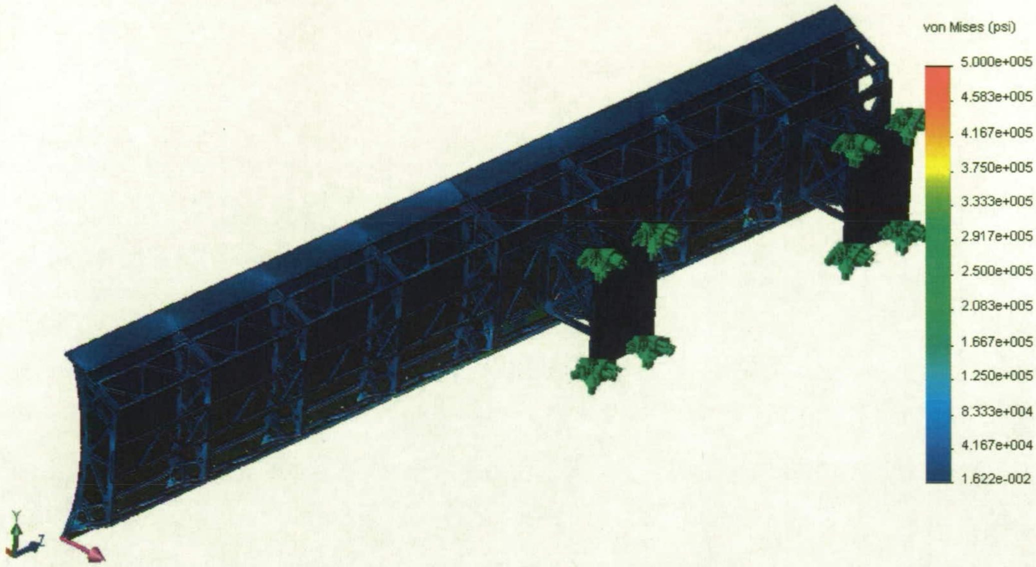

Figure 9 - vM stress in bonded model

The max displacement occurred at the tip of the blade where the force was applied. The URES displacement is shown in Fig. 10.

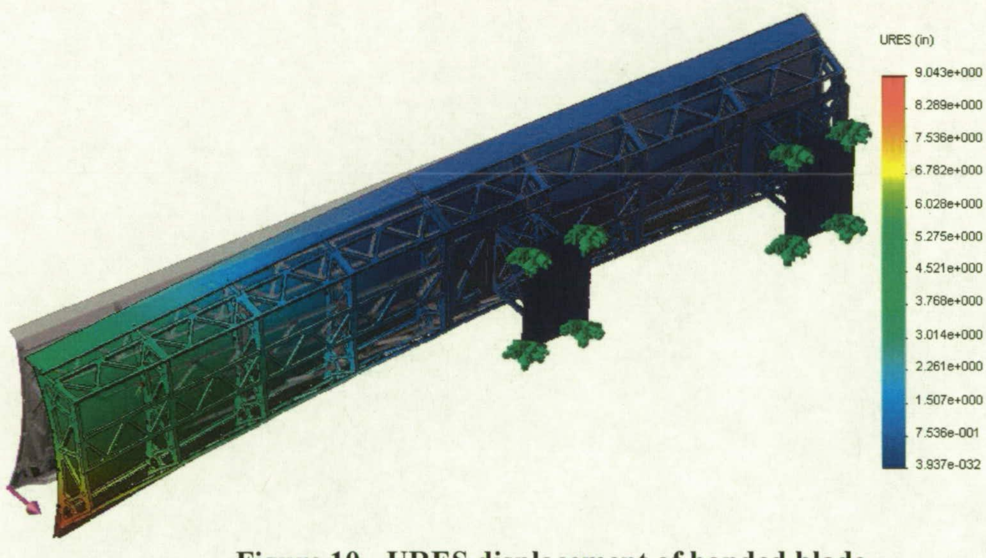

Figure 10 - URES displacement of bonded blade

V. MOSES LAKE TEST OVERVIEW

The Moses Lake field test took place on June 2008 at Moses Lake, Washington, USA. The area has rolling dunes consisted of lunar like sand. The sandy soil has a high cohesion due to the silt that settled there after the Mount St. Helens eruption and subsequent compaction due to weathering. Teams from the Surface Systems group at Kennedy Space Center, Human Robotics Systems group at Johnson Space Center and many other NASA centers and universities attended. They brought everything from rovers, attachments, and science experiments. The major goal was for each team to carry out operations to simulate lunar activates. This field test and many like it provide a unique experience for teams to perform integrated tests that cannot take place normally. In the case of the LANCE blade this lunar like area provided large areas to perform leveling and berm building activities. It is more cost effective to visit such field test sites and use the local in-situ materials than to manufacture, transfer and stage large quantities (1000's of tons) of lunar regolith simulant at a NASA center. The blade was used to simulate preparing a landing surface (Fig. 3) as well as a typical berm (Fig. 11). The tests were intended to: facilitate the systems integration of the LANCE blade to the Chariot interface, benchmark the operational performance and related times of the LANCE /Chariot system, and demonstrate that lunar site preparation is feasible with such a mobility platform. It is emphasized that the test did not attempt to do a high fidelity test of excavation in a lunar regolith space environment with related performance measurements. The actual performance will be dictated by additional factors such as 1/6th gravity, vacuum, electrostatics, regolith geotechnical properties and other environmental factors. This test was an operational in which many excavation methods were studied and experimented with in order to propose a feasible concept of operations to the NASA lunar surface systems architecture team.

Figure 11 - Chariot Mobility Platform using the LANCE Blade to Build a Berm in Moses Lake, WA.

The LANCE blade is one element of a growing system of lunar prototype hardware driven by the lunar outpost architecture. The Moses Lake field test provided a chance to perform integrated activities between a number of systems and robots (Fig. 12). Future work for lunar excavation will include systems designed to excavate regolith for the purpose of supplying oxygen production plants, automated universal attachment interfaces to switch between implements, and excavators with increased site preparation abilities.

Figure 12 - LANCE blade attached to Chariot (right) and ATHLETE with habitat (left)

While at Moses Lake the LANCE blade demonstrated its capabilities for leveling and clearing an area, as well as berm building. For the leveling and clearing operations LANCE was attached to the rear of Chariot and was driven from off-board the vehicle. Chariot made numerous passes over a designated 25m x 25m area to level the surface. The blade was then used in a back dragging function in overlapping passes to smooth out the final surface. It was observed that during the back dragging a slight yaw rotation of the vehicle allowed the material being removed to be pushed away from previously finished surfaces resulting in a higher quality finish. The time taken to clear the 25 m x 25 m area was approximately 2.5 hours. Grading operations are estimated to require a further 2 hours. During the berm building operations LANCE was used to build a 1.3m tall ramp style berm. The blade started out in a relatively flat area and began by dozing a pile of soil until Chariot reached wheel slip. From there Chariot took long shallow passes adding a layer of soil to the berm one at a time. This process slowly built up the ramp and reached a total berm height of about 1.3 meters. The time taken to build this berm was approximately 4 hours. It was observed that the site preparation activities were highly operator dependent, implying that significant training and expertise is required to skillfully remotely operate the LANCE/Chariot system. In addition, the point of view of the operator was important to ensure visual feedback. An off-board viewing position proved to be advantageous.

VI. Conclusion

The LANCE/Chariot system was developed at KSC, Florida and JSC, Texas by NASA and contractor engineers and then successfully integrated at Johnson Space Center. Analysis was performed by engineers and scientists at Glenn Research Center, and the Colorado School of Mines, joint testing was then conducted by KSC, JSC and GRC personnel at JSC. The LANCE development task showed how a geographically dispersed team can concurrently develop, design and test a new lunar excavation implement.

The field test results showed that the LANCE bulldozer blade mounted on a Chariot mobility platform is indeed a feasible element in a lunar architecture. Valuable operations lessons were learned and system characteristics were determined. The LANCE blade is 70 % lighter than an equivalent commercially available steel blade would be. However, the LANCE blade is a "proof of concept" prototype and further work remains to develop accurate lunar soil mechanics analysis techniques and to develop a lightweight blade with materials and control systems that can withstand the lunar environment.

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