Limiting Payload Deceleration During Ground Impact

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Abstract

THIS paper considers the problem of limiting the deceleration of balloon and sounding-rocket instrument payloads during ground impact by adding energy-dissipating, deformable structures. The basic physics of the two-step deceleration/energy dissipation process was analyzed and simple force and energy-balance relationships were developed. The pertinent equations were organized in a form that is conducive for computation. Two example problems, one of a sounding-rocket payload and the other of a balloon payload, are calculated and the results presented in the form of performance maps.

Contents

The high replacement value of sounding-rocket and balloon instrument payloads makes it imperative that they be recovered undamaged. The payload descends on a parachute, but parachute size limitations result in ground impacts with substantial velocity (20-25 ft/s). Energy-absorbing, deformable structures called crushpads may be attached to the base of the payload, thereby limiting the maximum deceleration during ground impact to a required level.

The mechanical behavior of the ground during compression is assumed to be that of a linear-elastic or Hooke material characterized by a soil coefficient called the subgrade modulus, K_{sg}, with units, lbf/in.^{2}/in. The ground develops a resisting force to a body of cross-sectional area, A, that is linearly proportional to the ground depression, δ_g.

Two payloads with the same mass and impact velocity but different size impact areas show the important result that the smaller impact-area body experiences a smaller maximum deceleration. In dissipating the same kinetic energy, of course, the smaller impact area gives a deeper penetration.

The maximum deceleration can be limited by crushpads of hexagonal cell, multicolumn, aluminum honeycomb which dissipate energy by plastic deformation parallel to the cell axes. The energy-absorbing property of the honeycomb is characterized by a coefficient called the crush strength, f_{cr}, which has units of lbf/in.^{2}. The honeycomb offers a constant resisting force to compression of $F=f_{cr}A_{cp}$, where A_{cp} is the cross-sectional area of the honeycomb crushpad. The crushpad absorbs energy $E=f_{cr}A_{cp}\delta_{cp}$ when crushed a distance δ_{cp}. This assumes that the crushpad is long enough so that it does not "bottom out" and become nearly rigid. The ideas just developed may be used to calculate the predicted maximum deceleration of a payload with crushpads impacting ground with a given subgrade modulus. Consider Fig. 1 in which the payload base impacts the ground. Four important lengths—the undeformed crushpad, ℓ_{cp}, crushpad deformation, δ_{cp}, payload penetration, $\delta_{p\ell}$, and total ground penetration, δ_g—are defined. Two impact situations are analyzed:

1. The base of the payload does *not* impact the ground. (All penetration is by the crushpad.)
2. The base of the payload penetrates the ground and the crushpad is buried.

The two situations were analyzed and the matching conditions between them determined.

Payload Does Not Contact the Ground, $\delta_{pl} < 0$

Initially the crushpad penetrates the ground until the deformed ground compressive stress reaches the crushpad strength, f_{cr}. The ground penetration stops and the crushpad deforms with a constant decelerating force. The kinetic energy and ground forces balance is calculated and two limiting cases are found:

1) The honeycomb crush strength is so high that it does *not* deform and all the energy is removed by ground deformation.

2) The ground subgrade modulus, K_{sg}, is so high that ground penetration is small and all energy is removed by deformation of the honeycomb.

Payload Contacts the Ground, $\delta_{p\ell} \geq 0$

The maximum decelerating force and the energy balance for this impact situation were formulated and calculated. There are also two limiting cases for this situation:

1) The payload just contacts the ground, $\delta_{p\ell}=0$.

2) The crushpads do not deform, $\delta_{cp}=0$. They act as rigid protuberances (or "spikes").

A value of K_{sg} above which the payload *does not* contact the ground, limiting case 1), can be calculated by matching situations 1 and 2. Calling this K_{sg} value $\tilde{K}_{sg}$, a crush strength, $\tilde{f}_{cr}$, is found below which the payload contacts the ground, regardless of the value of K_{sg}.

Limiting case 2) results in finding a maximum K_{sg} at which the payload contacts the ground. This is the value of K_{sg} at which case 1) of situation 1 must match limiting case 2) of situation 2. The crush strength, f^*_{cr}, corresponding to K^*_{sg} is the f_{cr} above which the crushpads act as rigid protuberances when the payload is in contact with the ground, $f^*_{cr}=2f_{cr}$.

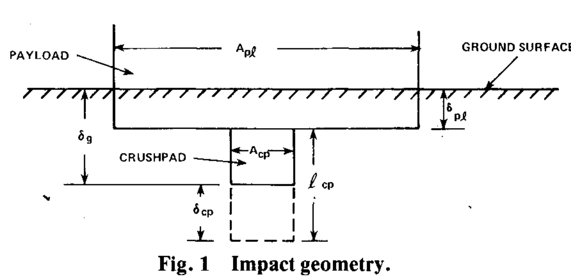

Fig. 1 Impact geometry.

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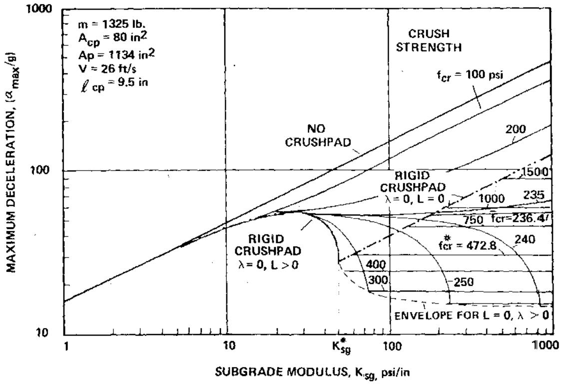

Fig. 2 Crushpad performance map for sounding-rocket payload.

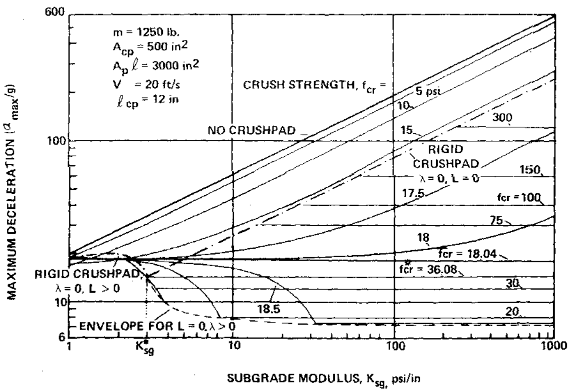

Fig. 3 Crushpad performance map for balloon payload.

Example 1: Sounding-Rocket Payload

Consider a sounding-rocket payload 38 in. in diameter ($A_{p\ell} = 1134$ in.^{2}), which has a mass $m = 1325$ lb. The parachute delivers the payload to the ground at 26 ft/s. The size of the crushpad structure is limited, because of instrumentation in the base of the payload and the length of the transition section between the payload and booster, to a total surface area $A_{cp} = 80$ in.^{2}, and length, $\ell_{cp} = 9.5$ in. beyond the base. It is desirable to find the maximum deceleration of the payload during impact with the ground (a_{max}/g) as a function of the subgrade modulus, K_{sg}, for various crush-strength (f_{cr}) crushpads. The results are presented in Fig. 2 in the form of a crushpad performance map. In Fig. 2 λ is a dimensionless crushpad deformation and L is a dimensionless depth of payload penetration.

The limiting case of rigid crushpads ($\lambda = 0$) was calculated from two formulas which give values that must match at the value of $K^*_{sg} = 49.8$ psi/in. The maximum deceleration at impact, a_{max}/g, was calculated using appropriate equations for the lower and upper regions of K_{sg}. Note that the rigid crushpad lowers the a_{max} compared with no crushpad because of the area affect discussed previously. This is about a factor of five when the payload does not contact the ground.

The rigid-crushpad line and the envelope for the payload just contacting the ground (L or $\lambda_{p\ell} = 0$) branch at $K^*_{sg} = 49.8$ psi/in., which corresponds to $f^*_{cr} = 472.8$ psi. For stiffer crushpads and increasing subgrade modulus, the impact peak acceleration, a_{max}/g, is determined first from the rigid crushpad line and then the a_{max} remains constant as the crushpad functions at its f_{cr} to absorb most of the impact energy. For crushpads softer than $f_{cr} = 236.4$ the impact a_{max} is higher for harder ground ($K_{sg} > 50$) as the crushpads deform more with increasing subgrade modulus and more of the energy is removed by deformation of the ground by payload penetration. However, for the intermediate range of f_{cr} values between 236.4 and 472.8 psi, the crushpads become more effective (lower a_{max}) with harder ground ($K_{sg} > 100$), until the crushpads deform fully.

Consider the Fig. 2 performance map and the specific examples of 750 and 300 psi strength honeycomb crushpad material. The maximum ground impact deceleration (a_{max}/g) for the 750 psi crushpad is about 45 g for K_{sg} greater than 130 psi/in. For subgrade modulus values below 130, the 750 crushpads behave as rigid crushpads with impact a_{max} levels as low as 25 g and as high as 55 g.

The softer crushpads using 300 psi strength honeycomb have a peak a_{max} of more than 50 g at a $K^*_{sg} = 26$, but the a_{max} drops to less than 20 g for K_{sg}'s greater than 75 psi/in. Since the impact areas at the White Sands Missile Range that are used for many sounding-rocket missions have coarse-grained, sandy silt soil with K_{sg}'s that measure between 100-400 psi/in., the 300-psi crushpads would seem to be an excellent selection.

Example 2: Balloon Payload

Balloon payloads do not have the severe size limitations on the crushpad structure that sounding-rocket payloads do. Consequently, the maximum deceleration of the balloon payload during ground impact can be limited to a much lower value than that for a sounding-rocket.

Consider a balloon payload which has a cross-sectional area of 3000 in.^{2} and a mass of 1250 lb. The crushpad area is 500 in.^{2} and ℓ_{cp} is 12 in. The parachute delivers the payload to the ground at 20 ft/s.

Figure 3 shows a crushpad performance map for the balloon payload. The calculation procedure is identical to that for the sounding-rocket payload described in example 1. It is seen that the performance map for the balloon compared with that of the sounding-rocket is shifted to more than an order-of-magnitude lower subgrade modulus. Impact deceleration in any but the softest of soil ($K_{sg} < 10$ psi/in.) can be limited to less than 10 g by using 20 psi crush-strength crushpads.

Summary

Two crushpad performance maps have been presented for use in determining the effectiveness of crushpad structures in providing "soft" landings for sounding-rocket and balloon payloads which are recovered using parachutes on land areas such as White Sands Missile Range. Sounding rocket payloads may be "cushioned" to peak loads (a_{max}/g) of less than 20 g and balloon payloads need not experience loads greater than 10 g during final impact.