The Stunt Person

Team 381

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Abstract

Cardboard boxes are common, almost mundane items. At work, at the post office, or at the grocery store, one may run into dozens of them every day. But the average motorcycle stuntman may run into dozens of them in a handful of seconds. The movie industry commonly exploits these inexpensive shock absorbers to pull off their death-defying jumps, falls, and crashes. Unfortunately for stunt coordinators, little is known about their behavior under dynamic and impulsive loading. Cardboard is not even regarded as an engineering material, due to its inconsistency of material properties.

In this paper, we present an innovative new method combining the pre-existing industry strength ratings with elements of shock absorption theory. This method, derived from physical principles and mathematical technique has been supported by experimental data. Our model calculates the work necessary to deform a cardboard box into the characteristic buckling pattern in order to determine the energy absorption capacity of the box. We then use shipping industry ratings to approximate the unavailable material properties of the cardboard.

This simple and elegant model easily lends itself to crash pad optimization. It provides flexibility in simulating different riders, boxes and jump geometries with concise, efficient coding and quick computation time. This method, simple in its approach, nevertheless provides compelling solutions to the problem at hand.

1 Introduction

Stunt coordination can prove to be a very difficult task. Movies today require bigger and better stunts than those of old. Determining the best means of protecting stunt people as well as allowing for spectacular results is a critical job for movie producers. Despite this, most movie stunts are designed by seasoned stunt coordinators through a combination of experience and intuition. Stunts are generally over-designed on the side of safety, which wastes money, and may cause filming difficulties in cutting landing pads and protective equipment out of the scene.

In this problem, the script calls for an exciting motorcycle chase scene, culminating with a death-defying jump over the back of an elephant. Unseen by the camera, the stunt double and his bike will land safely in a pile of cardboard boxes on the other side of the protruding pachyderm. But first, the crash pad needs to be created by determining the optimal number, size, and stacking geometry of the boxes. It is desirable to use as few boxes as possible in order to minimize cost and visibility of the pad.

Using cardboard boxes as the absorption medium presents a unique challenge. Impact engineers have derived methods for calculating the buckling modes and energy absorbed by square beams in compression. Pre-existing heuristics can be used to model impulses and sudden collisions. However, these methods favor plastic materials with well-defined properties. The properties of corrugated paperboard are poorly understood and may vary based on any number of factors, including manufacturing process, quality of the kraft and wood fiber used, relative humidity, and age. Not regarded as a valid engineering material due to these variabilities, there is little to no material property data available.

However, the shipping industry depends on the strength, minimal weight and low cost of corrugated cardboard. Transport conditions, which include stacking the boxes on large pallets, necessitate an alternate method of quantifying box performance. Formerly, boxes were rated by the Burst Test, or the amount of stress necessary to fail a box. A more current standard is the Edge Crush Test (ECT), the maximum amount of force per unit length necessary to cause the sides of the box to fail. The ECT is directly related to the Box Compression Strength (BCS), or the maximum amount of force the box can withstand. Normally, BCS is used to determine how boxes can be stacked on palates without sustaining damage. Unfortunately, they give little information about the performance of the crates under dynamic loading.

Instead, custom drop tests are performed to rate the resistance of a loaded box to a drop from an arbitrary height. These tests are performed as desired, and there are currently no standards for the impact resistance of a given box. In the shipping industry, subjecting boxes to impulsive loading is generally undesired, and so there has been little investigation into this failure regime.

Neither dynamic crushing theory nor load analysis is sufficient to describe the peculiarities presented by this problem. One lacks material data, the other lacks the robustness. Since no existing algorithm can accurately model this system, a new one will have to be developed.

2 Assumptions

In solving this problem, we need to make the following assumptions:

1. Our elephant is nine feet tall.
2. All cardboard boxes are initially undamaged.
3. There are negligible variations among individual cardboard boxes.
4. The cardboard is strain-rate insensitive.
5. After impact the boxes are in one of three states: undamaged, partially damaged, or fully crushed.
6. All cardboard boxes remain in the pile.
7. We will model the motorcyclist as having a rectangular profile as viewed from directly below the bike.
8. The cost of a cardboard box is directly proportional to its volume.
9. No penetration will occur, as we assume all forces involved are blunt forces and the motorcycle's wheels are stopped upon impact.
10. The biker will reach the apex of his jump directly over the elephant.
11. Crushing is defined as the box crumpling to 27% of its original height.
12. The biker will keep the motorcycle oriented at approximately the angle of his launch ramp throughout the course of the jump.

3 Buckling, Bursting or Squashing?: Formulating the Model

Although corrugated cardboard has excellent strength for its weight and cost, it is not considered an engineering material because of inconstancy of its material properties. As a result, theoretical failure analysis is rarely used to analyze the performance of cardboard structures. Instead, the cardboard industry has come up with a series of standards for strength rating. Originally, the Burst Test (BT) was the primary strength rating. A test box placed between parallel plattens receives a slowly increasing load until complete failure. The final load is divided by the area of the top of the box to determine BT. This metric is being replaced by Edge Crush Test, or ECT. ECT is directly related to Box Compression Strength (BCS), the stress necessary to cause box failure. ECT is measured by taking a single piece of cardboard, and applying force to the edge until buckling occurs. This results in a value of force per unit length. ECT is related to BCS by the McKee equation [2]:

$$\mathrm{BCS} = 5.87\ \mathrm{ECT}\sqrt{Pt} \tag{3.1}$$

where P is the perimeter of the top of the box $(2L + 2W)$, t is the thickness of the cardboard, and the 5.87 is the fluting constant, related to the corrugations of the cardboard itself. This equation was developed in 1963, and is used as the standard way of calculating box strength. It was derived by approximating the box as four simply-supported plates of infinite length, assumed to fail through elastic buckling. It is regarded as valid so long as the perimeter is less than seven times the depth and the length-width ratio should be less than three. Today, the McKee equation is the simplest and most common way to compute BCS. Although larger shipping firms may own commercially-available software that performs a more complicated analysis, McKee is still the industry standard.

There are two obvious and well-known flaws in McKee's formula. The first is that depth is not taken into account. For boxes where the depth is greater than one-seventh of the perimeter, the infinite plate assumption is generally valid. Secondly, the formula cannot distinguish between two boxes of equal perimeter but of different length-to-width ratios. It treats every box as an equivalent square box. This can yield an error of 6-18

A researcher named Windaus theorized that the strength of is proportional to $\sqrt(L/W)$. His formula, published in 1976 stated that

$$\frac{P_r}{P_s} = \frac{2\sqrt{L/W}}{(L/W+1)} \tag{3.2}$$

where P_r and P_s are the respective strengths (BCS) of a rectangular and square box with equal perimeters.

A more detailed formula for BCS has been developed by Thomas Urbanik. [7] His algorithm is based on nonlinear, inelastic theory and is considerably more accurate than the McKee formula. Unfortunately, the algorithm requires accurate values of elasticity modulus in the x- and y-directions, the mean Poisson's ratio and the in-plane shear modulus of elasticity. Although the algorithm can be used (with reduced accuracy) without the latter two quantities, the moduli of elasticity were still not available to us. Furthermore, despite the increased accuracy of the algorithm, it is still only a static method, and so its performance in a dynamic situation is unpredictable. For these reasons, we chose not to pursue this algorithm further.

Since we desired a model which would incorporate the dynamic nature of the problem, we turned to the field of crash-worthiness and impact engineering. Often, hollow tubes are used as "mechanical fuses," i.e., they are sacrificially crushed in order to absorb energy in an accident. The w-shaped guard-rails commonly seen on roadsides are one such example. Some race cars incorporate "crash boxes" on the front bumper to take the brunt of a collision. [3]

To correctly model our boxes, we researched the dynamic crushing mode of a thin-walled, square tube. To develop this model, we must begin with a static crushing mode. When a tube is crushed, it forms a series of wrinkles, or lobes. The energy absorbed by the tube is equal to the amount of energy to form these nodes. To calculate the energy used to form one node, is it useful to visualize the node as a hinge, as pictured in Figure 1. From the definition of work, force times distance, the work necessary to collapse one wrinkle is $2lP$ where P is the axial force. The equivalent energy to performing this feat is broken up into three parts. The first part is rotating the hinge:

$$E_1 = 2 \cdot 4WM_0\frac{\pi}{2} \tag{3.3}$$

where M_0 is the plastic collapse moment per unit perimeter, $4W$ is the perimeter, and $\frac{\pi}{2}$ is the angular distance traveled by each half of the hinge.

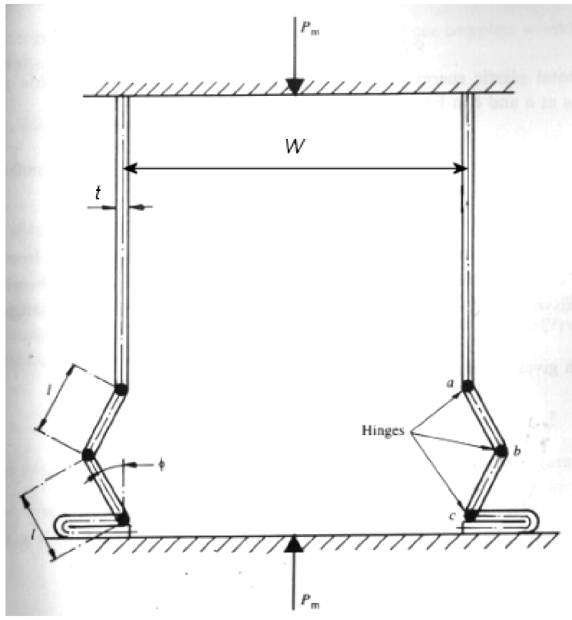

Figure 1: Buckling Mode. Modified from [4], Fig. 9.7

M_0 can be found using a material property known as the plastic flow stress, σ_0, meaning the stress at which the material will begin to deform without returning to its original shape.

$$M_0 = \sigma_0 t^2/4 \tag{3.4}$$

The second form of energy comes from moving Point b of the hinge from W to $W + l$. Incrementally:

$$dE_2 = 4(W/2 + l\sin(\phi))M_0(2d\phi) \tag{3.5}$$

Integrating from $\phi = 0..\frac{\pi}{2}$ yields

$$E_2 = 8M_0(W\pi/4 + l) \tag{3.6}$$

The final energy term comes from the stretching of the material that occurs because the perimeter of the lobes is larger than that of the original tube. The differential strain developed in the tube can be expressed as follows:

$$d\epsilon = \frac{4(l/2)\sin(\phi + d\phi) - 4(l/2)\sin(\phi)}{4W} \tag{3.7}$$

which can be simplified to

$$d\epsilon = l\cos(\phi)d\phi/2W \tag{3.8}$$

when $\sin(d\phi) \implies d\phi$ and $\cos(d\phi) \implies 0$. The strain energy absorbed as from ϕ to $\phi + d\phi$ is

$$dE_3 = \sigma_0 d\epsilon 2lt(4W) \tag{3.9}$$

Substituting (3.8) for $d\epsilon$ and integrating from 0 to $\pi/2$ yields

$$E_3 = 4\sigma_0 l^2 t \tag{3.10}$$

Combining (3.3),(3.6) and (3.10) and equating them to the work done by the crushing force, we get the following equation.

$$2lP = 2 \cdot 4WM_0\frac{\pi}{2} + 8M_0(W\pi/4 + l) + 4\sigma_0 l^2 t \tag{3.11}$$

Minimizing the axial crushing force, or setting $dP/dl = 0$ yields

$$P = 13.05\sigma_0 t^2 (W/T)^{1/3} \tag{3.12}$$

In order to account for the dynamic properties of this situation, the theory suggests adding a component based on strain rate sensitivity, modifying (3.12) to

$$P = 13.05\sigma_0 t^2 (W/t)^{1/3}[1 + (0.33V/CD)^{1/q}) \tag{3.13}$$

where V is the velocity of a mass M striking the tube. D and q are constants determined by the strain rate sensitivity of the material. Unfortunately, because of its brittle nature, we are assuming cardboard to be strain rate insensitive. In this case, $D \implies \infty$, and so (3.12) can be used instead.

Part of this theory also contains the restrain that because the buckled material tends to pile up, the tube can only compress such that its final height is about 27% of its initial height. Unfortunately, being unable to obtain the derivation of this statement (cited by /citeJones), we have to take the author at his word. However, intuitively, it seems to be a reasonable assumption.

This also seems to imply that McKee and Urbanik (except for the lack of material property) might be valid after all, since there seems to be little

Figure 2: Testing

different in a slow crush vs. a fast one. Another problem is that (3.12) requires the plastic flow stress, σ_0. We substituted ECT$/t$ for σ_0, since that is the stress at which the cardboard begins to deform. A second problem with the crush model is that, like the McKee formula, it is only given for square boxes. We replaced the W term in (3.12) with $\frac{L+W}{2}$, to get the average length of a side instead. Also, we theorized that the Windaus correction formula might be valid for this situation, as well.

At this point in our modeling process, we had two possible models, and a correction factor which may or may not be useful. In order to make an informed model selection, we needed physical data. We designed an experiment in which we would drop a known mass from a known height onto a variety of cardboard boxes. We would use each of our models to predict the amount of energy each box could absorb. By comparing the kinetic energy of the dropped mass to the predicted absorption energy, each model would yield a prediction as to whether or not each box would break.

For these tests, we dropped a box of text books weighing 28 pounds from a height of 36 inches. Photographs of each test subject are shown in Appendix 2.

Results were as follows:

McKee did a pretty poor job of estimation, even in its modified form. Although some of the boxes did not hold to the $P < 7D$ criteria, this had little bearing on whether or not McKee would correctly predict breakage.

Box #	Length (in)	Width (in)	Depth (in)	ECT (lb/in)	thickness (in)
1	13.25	10.625	6.5	32	0.138
2	19.3125	11	20.875	32	0.157
3	36.75	12.75	8	32	0.118
4	6.375	6.375	6.5	32	0.118
5	5.375	7.25	4.75	32	0.079
6	6.375	10	4.375	32	0.118

Box #	McKee	Adj. McKee	Crush	Adj. Crush	Damage
1	226.81%	225.44%	119.86%	119.13%	Full
2	877.44%	843.80%	455.61%	438.15%	None
3	372.14%	325.47%	169.73%	148.45%	None
4	153.45%	153.45%	87.74%	87.74%	Slight
5	91.11%	90.10%	48.77%	48.23%	Moderate
6	117.05%	114.15%	64.20%	62.60%	Full

Table 1: Raw Data and Results From Box Crushing Experiment,Box 3 had a divider; we added this extra perimeter to Length. In reality, the box was only 18.375in long. See Appendix 2 for picture.

On the contrary, although it tended to underestimate the strength of the boxes, the Crush method did a good job of predicting whether or not the box would begin to break, which is actually a more desirable criteria for our model. In all but one case, if the Crush model prediction was more than 100%, the box completely survived the the impact. This means that any box with a prediction of less than 100% would definitely break, which is the case in which we are most interested.

4 Gentlemen, Start Your Engines!: Modeling the Launch Configuration

We assume the problem is posed in the following manner. We are given a launch ramp with angle, θ, from the horizontal. The motorcycle will leave the launch ramp at height h, assumed to be greater than nine feet, the height of the elephant. For maximum excitement, we assume our motorcyclist, Jim, will reach the peak of his jump directly over the elephant. Using this and the given horizontal distance, x, from the edge of the launch ramp to directly above the center of the elephant, we calculate the speed at which Jim must leave the ramp using Newton's laws as:

$$|\vec{v}_0| = \sqrt{\frac{gx}{\cos\theta\sin\theta}} \tag{4.1}$$

, where g denotes gravitational acceleration. In stopping Jim, we will mount a rectangular container tightly filled with boxes along a landing ramp. We would like to create our ramp and adjust our box container so that the biker will strike the boxes perpendicular to their surfaces. Our model is designed for the boxes to collapse in this orientation, which is known to be the optimal absorption orientation. Furthermore, hitting the boxes head on will decrease the probablilty of hitting the boxes tangentially, causing them to fly out of the array. To accomplish this, we note that the direction of the biker's velocity vector is at an angle, θ, with the horizontal again at horizontal distance 2x from the launching ramp and vertical distance h from the ground. It is at this point that we would like impact with the center of the boxes to occur.

In order to achieve this result, the landing ramp will be constructed with angle $90 - \theta$ with the horizontal(Figure 2). As we vary the height, h2, of the boxes, we will move the ramp to the left or to the right and the boxes

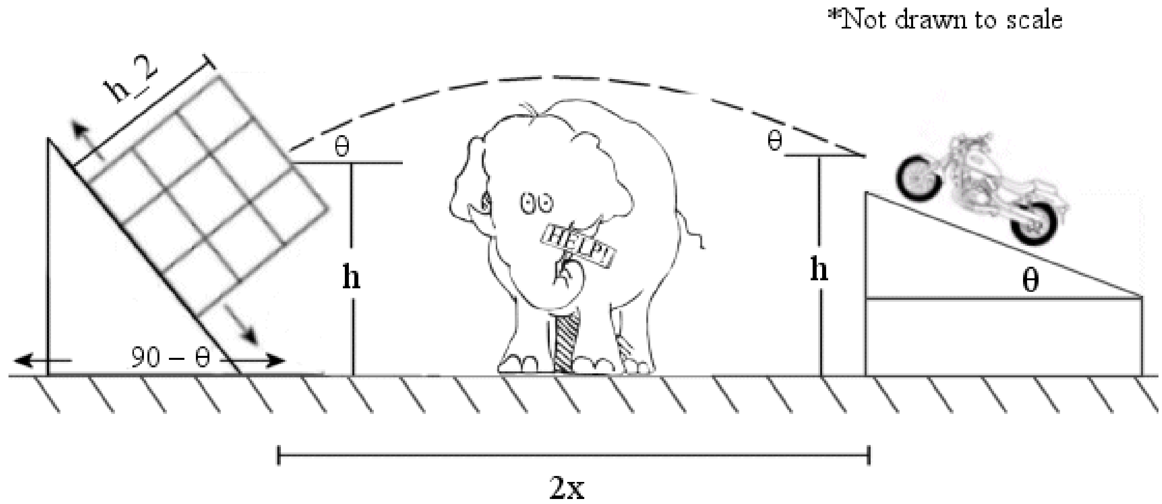

Figure 3: Generic Jump Geometry

along the ramp so as to orient the center of the boxes to be in the desired location(Figure 3).

5 Ready, Set, Code!: Implementation of the Model

The process of deciding on the most important features to the director was a difficult one. We identified two possible goals for optimization:cost and visibility. After pricing several box sizes, we concluded that due to the low cost of cardboard boxes[8], visibility is the primary concern. We would like to provide the director the ability to film the scene from as many different angles as possible. Therefore, we chose to minimize the surface area of the stack of boxes. To accomplish this, we wrote code (Appendix A) using GNU octave software. In addition, our code will simulate the crash of the motorcycle.

We will begin by describing the process of the simulation. To run the simulation, we need several pieces of information. We require the dimensions, thickness, and the ECT of the box. Using this, we use the Crush Theory test (3.12) and Windaus correction (3.2) to determine the kinetic energy needed to fully crush a box. We then calculate the velocity of the biker as he travels through the pile of boxes using conservation of total energy. On each level of the stacked boxes, the rider will lose kinetic energy in the amount of the number of boxes with which he comes in contact multiplied by the kinetic energy necessary to fully crush one box. We repeat these collisions until the motorcyclist does not have sufficient kinetic energy remaining to fully crush the next row of boxes. This indicates to us the depth to which the biker will drop within the stacked boxes.

The next task for our program is to find the optimal box size given the rider's mass and his velocity upon impact with the boxes. Due to the geometry of our arrangement, the motorcyclist will have the same kinetic energy upon impact with the boxes as when he leaves the ramp. Also, his trajectory will be perpendicular to the surface of the boxes. An additional assumption was made that the biker will maintain his motorcycle atan angle of θ upon his collision. This will result in both wheels of the motorcycle making contact with the stack of boxes simultaneously. Thus, this greatly simplifies the problem as each new row of boxes encountered is directly below the previous. Hence, to perform the optimization, we give the optimization routine the mass of the biker and his initial velocity departing from the ramp. Next, we simulate the crash for box sizes with combinations of length, width, and height between 4 and 36 inches, the standard available box sizes. We discard all situations where the rider decelerates quickly enough to result in injury. The biker's deceleration rate is calculated using:

$$a = -\frac{\text{BCS}}{M} \tag{5.1}$$

where BCS is the box compression strength(3.12), and M is the mass of the biker and the motorcycle combined. We have run trials with acceptable deceleration rates ranging from three to six times gravitational acceleration(Table 2). This simulation was performed with a rider of 15.528 Slugs entering the boxes at $44\frac{\text{ft}}{\text{sec}}$. These values can easily be adjusted to fit other situations.

6 Adjusting our Safety Net: Strengths and Weaknesses of the Model

As with every model, ours has several weaknesses. Many are due to the mercurial nature of cardboard itself. We cannot account for humidity, age,

Maximum force on rider	optimal box size
3g	12"X10"X7"
4g	12"X7"X6"
5g	12"X5"X5"
6g	12"X5"X5"

Table 2: Optimal Box Sizes for Various Safety Limits

glue type, construction or peculiarities of specific boxes. They are assumed to be isotropic, although this is certainly not the case. Furthermore, the basis of our model is a theory which has been generated for engineering materials such as steels or carbon composites. These materials have distinctive stages of deformation, including elastic and plastic deformation. They have well-defined elastic moduli, yield strengths, Poisson's ratios and strain rate sensitivities. Cardboard has none of these properties.

There is a solution to this problem, although it is not one we are capable of implementing. A movie studio interested in quantitatively designing crash pads should first do a comprehensive study of the brand of cardboard boxes they use. They should always buy boxes from the same provider, makes sure that they are informed of any manufacturing changes the provider may implement, and continue to spot test box properties within every box shipment. In fact, it could be quite lucrative for a box company to devote themselves solely to creating "crash boxes," which may have extra features implemented to better absorb kinetic energy without providing too large of a resistive force. However, we feel confident in our model because it predicted laboratory-tested results. If it had not performed well, we would not have used it.

Upon further study, it could be found that our model is not the best representative of box strength. With more available box properties, the Urbanik model could be computed, which could provide a more accurate picture. There are other models, such as Maltenfort's statistical model, or the Podstavkina correction [7], which may also work; we were unable to find the papers in question and so were reluctant to include these models in our study. Nevertheless, our method of developing a model and then testing it against experimental values is a sound one.

Furthermore, there were multiple sources of error without our actual experiment. It was difficult to obtain boxes on such short notice, so our sample space came from a number of different sources. Furthermore, most of our boxes had already been used for shipping, so they may have been pre-stressed. Several had significant quantities of packing tape on the box. Also, the cardboard thickness varied in different parts of the box, which made it difficult to get accurate measurements. In more controlled conditions, we would have obtained all our boxes fresh from the same source (the same source from which we intended to obtain our actual crash boxes). With more time, facilities and funding, we would be able to create a much more comprehensive collection of data with which to correlate our model.

As for our particular model, it tends to underestimate the energy absorbed by an individual box. The crush model tends estimate the amount of energy needed to begin crushing a box, rather than to completely crush a box. This is could be seen as an advantage, because it tends to give a conservative estimate of the number of boxes necessary in a given array. Unfortunately, this may also result in a situation in which the boxes may be stronger than estimated. In this case, they may not break, which could cause injury to the stuntman. For this reason, we recommend that a relatively low "safe acceleration" be used. Although humans can easily withstand a 5g acceleration, it is better to set the maximum acceptable acceleration to 3 or 4g in the program.

A second failing of the model is that we have not taken into account the possibility of perferation. It is certainly possible that instead of crushing a box, part of the motorcycle may plunge right through the top. (See Figure **??**). The box will still absorb some of the blow, but we cannot guarantee that it will perform as well as a box in normal crush mode. Fortunately, as long as the boxes are smaller than the size of the motorcycle, the bike will catch the sides of several boxes, and will not plunge completely through a layer. Therefore, perforation can only occur on the topmost layer. As a recommendation, if the boxes are larger than any protruding part of the motorcycle (such as a wheel), an extra layer of boxes should be added to the stack as a precaution against potential perferation.

The jump geometry model has weaknesses as well. We have designed our angled crash pad because in that orientation, the energy absorption of the boxes is maximized. However, based scenery restrictions, there may not be room to place the crash pad in its optimal position. Furthermore, we have assumed that the rider will be using a ramp, rather than riding off a raised platform, or some other method. Unfortunately, in order to create a model,

Figure 4: Box 2 Post-Perferation

we had to create some sort of physical set up, and this is the one we chose.

The model does have many strengths, however. First and foremost, it has tested successfully against real results. Based on energy methods, our model is well-suited to the solving the problem at hand, which simplifies much of the later programming. The model was designed for the quasi-static situation of dynamic loading, rather than the straight static model usedby McKee and Urbanik. Furthermore, as more cardboard data becomes available, the algorithm can be made more accurate by replacing ECS with σ_0, and removing the assumption that cardboard is strain rate independent.

Many of the strengths of our model are in its implementation. It is simple to use; the code relatively short, and computes quickly. Our particular code runs through every box dimension (for each of length, width and depth) between 4" and 36" in increments of 1" (commonly available sizes). Length and width are assumed to be interchangable, which means that the program runs through 5120 different boxes. However, the maximum runtime of the program is under a minute on a G3 500. The model is also easily adaptable. Rider weight, jump distance, jump height, acceptable acceleration, and available box sizes can all be altered in our program for a custom situation.

A Code

```
#!/usr/bin/octave -q

%GNU Octave code- team 381
%
%This program simulates the collision of our biker and boxes.

function [nx,ny] = next_box(x,y,theta)
  %[nx,ny] = next_box(x,y,theta)
  %
  %As the rider moves throught the boxes, this procedure
  %tells where he hits next

  xb = floor(x);
  yb = floor(y);
  if(floor(y+tan(theta))<yb+1)
    ny=y+tan(theta);
    nx = xb+1;
  else
    nx = xb+(yb-y+1)/tan(theta);
    ny = yb+1;
  endif
endfunction

function vf = impact(vi,mass,cb,num)
  %vf = impact(vi,mass,cb,num)
  %
  %This procedure computes the velocity after he
  %impacts a box.

  vf = sqrt(vi^2-2/mass*cb)/sqrt(num);
  if(vf != real(vf))
    vf = 0;
  end
endfunction

function [endx,endy,num_boxes] =
```

```
                    run_sim(x0,y0,theta,mass,v0,cb,length,width)
  %[endx,endy,num_boxes] =
  %               run_sim(x0,y0,theta,mass,v0,cb,length,width)
  %
  %This procedure runs our mass into a box. It returns the
  %ending position of the mass as well as the number of boxes
  %crushed in the procedure.
  %The coordinates x and y are in number of boxes.

  v = v0;
  num_boxes = 1;
  while(v > 0)
    num = num_boxes_rider_hits(length,width);
    v = impact(v,mass,cb,num);
    [xn,yn] = next_box(x0,y0,theta);
    x0=xn;
    y0=yn;
    num_boxes = num_boxes+1;
  endwhile
  endx = x0;
  endy = y0;
endfunction

function cb = get_energy_to_crush(L,W,D,ECT,t)
  %cb = get_energy_to_crush(L,W,D,ECT,t)
  %
  %First we calculate out crush test, then
  %run the windaus correction and convert that to
  %energy needed to crush the box
  crush_test = 13.05.*ECT.*t.*((L+W)./2./t).^(1./3);
  windaus = 2.*sqrt(L./W)./(L./W+1).*crush_test;
  cb = windaus.*.73.*D;
endfunction

function nb = num_boxes_rider_hits(l,w)
  %nb = num_boxes_rider_hits(l,w)
  %
  %Given the size of the boxes,
```

```
  %how many will our rider hit on each level.
  rider_width  = 12;
  rider_height = 58;

  nb = ceil(rider_width/l)*ceil(rider_height/w);
endfunction

function ret = to_min(s)
  %ret = to_min(s)
  %
  %Find the dimensions of the boxes over values of s
  %Which minimize the total height of the stack

  ret = 1000;
  mass = 15.528;  %mass of the rider
  veloc = 44;     %initial velocity of the rider

  % Search all three directions f or the best box size
  for l = s
    for w = linspace(s(1),l+1,l-s(1)+2)
      for d = s
%exclude those that do not pass the reasonable dimensions
%criteria.
if((2*(l+w) < 7*d) & (l < 3*w))
  % Find the energy needed to crush the boxes that he hits
  cb = get_energy_to_crush(l,w,d,32,.13);
  % More than this would hurt him
  if(cb*num_boxes_rider_hits(l,w)/(.73*d) < 2500)
    [x,y,nb]=run_sim(0,.5,0,mass,veloc,cb,l,w);
    if(nb*d<ret)
      ret = nb*d
      [l,w,d]
    end
  end
end
      end
    end
  end
```

```
endfunction

function mh = find_min_height(a,b)
  %mh = find_min_height(a,b)
  %
  %This procedure sets up the parameters and calls
  %to_min(). Use this to find the optimal
  %dimensions between a and b.

  s = linspace(a,b,b-a+1);
  mh = to_min(s);
end

function main()
  %we begin by calling the procedure to find
  %the optimal dimensions of the box

  ret = find_min_height(1,36)

  %We can also run a test with and parameters
  %we wish this way

  %Size of a box
  length = 12;
  width  = 11;
  depth  = 7;
  mass = 15.528;  %mass of the rider (slugs)
  veloc = 44;    %initial velocity of the rider ()

  cb = get_energy_to_crush(length,width,depth,32,.13);

  [x,y,nb]=run_sim(0,.5,0,mass,veloc,cb,length,width)
end

main();
```

Figure 5: Box 1

B Images

Figure 6: Box 2

Figure 7: Box 3 (before)

Figure 8: Box 3 (after)

Figure 9: Box 4 (after)

Figure 10: Box 5 (after)

Figure 11: Box 6 (after)

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