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A METHOD FOR RELATING IMPACTS WITH YIELDING AND UNYIELDING TARGETS*

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ABSTRACT

The public has questioned the severity of the regulatory 9 meter drop onto an unyielding target required for Type B radioactive material shipping packages since this drop height results in an impact velocity of only 13.3 m/s (30 MPH). It is the unyielding nature of the regulatory target which makes the 9 meter drop so severe. In this paper a method for relating higher velocity impacts with yielding targets to impacts onto an unyielding target is developed. The severity of impacts with yielding targets is decreased by the amount of the impact energy absorbed in damaging the target. There have been previous attempts to correlate impacts with yielding targets to lower velocity impacts onto an unyielding target[1,2,3], and this work is an expansion of those efforts.

BACKGROUND

There are several reasons for wanting to relate the severity of impacts with yielding targets to that of impacts with an unyielding target. The motivation for making the comparison will somewhat dictate the way the comparison is made. In NUREG-0170[1], which is a risk assessment for the shipment of all types of radioactive material, the properties of the packaging were not known. This forces the relationship between impact velocities for yielding and unyielding surfaces to be independent of package stiffness. For this reason a method was developed that compared the penetration of a rigid sphere into different surfaces, with steel considered to be the unyielding target. Velocities resulting in equal penetration depth were considered to be equivalent.This led to the following relationship to determine equivalent impact velocities:

$$\frac{V_{yielding}}{V_{steel}} = \left[\left[\frac{1-\nu_y^2}{1-\nu_s^2}\right]\left[\frac{E_s}{E_y}\right]\right]^{1/3} \qquad \text{(EQ 1)}$$

where $V_{yielding}$ is the velocity for impact onto a yielding surface, V_{steel} is the velocity for impact onto an unyielding surface, ν_y and E_y are Poison's ratio and Young's modulus for the yielding surface material, and ν_s and E_s are Poison's ratio and Young's modulus for steel. This method was only applied to aircraft accident scenarios and the distribution of target hardness was determined by the ground surface composition along airline flight paths.

In the Modal Study[2], a risk assessment for the transport of spent fuel, the properties of the package were known. This allows the relationship between yielding and unyielding targets to depend on package system. To determine equivalent impact velocities an equivalent damage technique was used. This technique resulted in a relationship for velocities of:

$$\frac{V_{yielding}}{V_{unyielding}} = \sqrt{1+\frac{d_s}{d_c}} \qquad \text{(EQ 2)}$$

where $V_{unyielding}$ is the impact velocity for impacts onto an unyielding surface, d_s is the deformation of the yielding target caused by an impact of a rigid package at a velocity such that the impact force is the same as for the impact of the package on an unyielding target, and d_c is the deformation of the package caused by impact on an unyielding target.

METHOD

The method for relating impacts with yielding targets to an impact with an unyielding target discussed in this paper will apply the principal of conservation of energy. Immediately before the impact the energy of the package and target is equal to the kinetic energy of the package. At the point of maximum deformation of the package and target the velocity is zero, so all of the energy in the system is strain energy. For impacts onto a rigid target the strain energy of the system is all in the package. During an impact with a real target the strain energy of the system is in both the package and the target. For casks, the strain energy in the package is typically divided into strain energy in the impact limiter and strain energy in the cask body, with the strain energy in the impact limiter typically being orders of magnitude larger than the strain energy in the cask body. If inertial effects are ignored the force acting on the cask body is the same as the force acting on the impact limiter and target for any time during the impact event. This condition can be viewed as a spring-mass system with a set of three massless nonlinear springs acting in series. Figure 1 shows this simplification of the impact event. Notice in this figure that the impact limiter and target are treated as massless. For the impact limiter this assumption is generally quite accurate because its mass is usually much less than the mass of the cask. Neglecting the mass of the target in most cases does not introduce a large error in the analysis because the velocity, and therefore kinetic energy, of this mass is usually very small.

The strain energy in each of the springs for a given displacement is equal to the area under the force-deflection curve up to that displacement. For a linear spring this results in the

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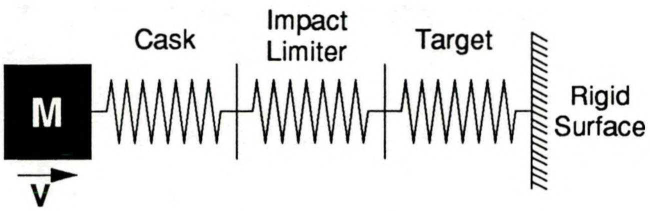

Figure 1 - Simplified spring model for impacts.

familiar equation $E = 1/2K\delta^2$, where E is the strain energy in the spring, K is the linear spring constant, and δ is the displacement of the spring. For a non-linear spring with a force-deflection relationship defined by F(x), equation 3 shows the mathematical expression for the strain energy:

$$E = \int_0^{\delta} F(x)\,dx \qquad \text{(EQ 3)}$$

Where:

- E = The strain energy in the spring.
- F(x) = The force in the spring as a function of displacement.
- x = The displacement of the spring.
- δ = The displacement of the spring at the force level of interest.

In the system depicted in Figure 1, the total strain energy of the three springs must be equal to the kinetic energy of the mass at impact, and the force in the three springs is equal. These two conditions are the constraints on the problem and may be expressed mathematically as:

$$\frac{1}{2}MV_{yielding}^2 = E_c + E_l + E_t \qquad \text{(EQ 4)}$$

and

$$F_c = F_l = F_t \qquad \text{(EQ 5)}$$

where M is the mass of the cask and impact limiter, $V_{yielding}$ is the impact velocity onto a yielding target, E_c, E_l, and E_t are the strain energies in the springs representing the cask body, impact limiter, and target, and F_c, F_l, and F_t are the forces in these springs.

For impacts onto an unyielding target the entire kinetic energy of the mass must be converted into strain energy of the cask and impact limiter. This implies that the strain energy in the springs representing the cask and impact limiter is equal to the kinetic energy of the mass for an impact onto an unyielding target. Expressing this mathematically:

$$E_c + E_l = \frac{1}{2}MV_{unyielding}^2 \qquad \text{(EQ 6)}$$

where $V_{unyielding}$ is the impact velocity onto an unyielding target. Equations 4 and 6 can be combined to provide a relationship for velocities of:

$$\frac{V_{yielding}}{V_{unyielidng}} = \sqrt{1 + \frac{E_t}{E_c + E_l}} \qquad \text{(EQ 7)}$$

EXAMPLE PROBLEM

The method described above will be demonstrated with the following example problem. A 90,700 kg (100 ton) rail cask impacts a hard soil with a velocity of 26.8 m/s (60 MPH). The

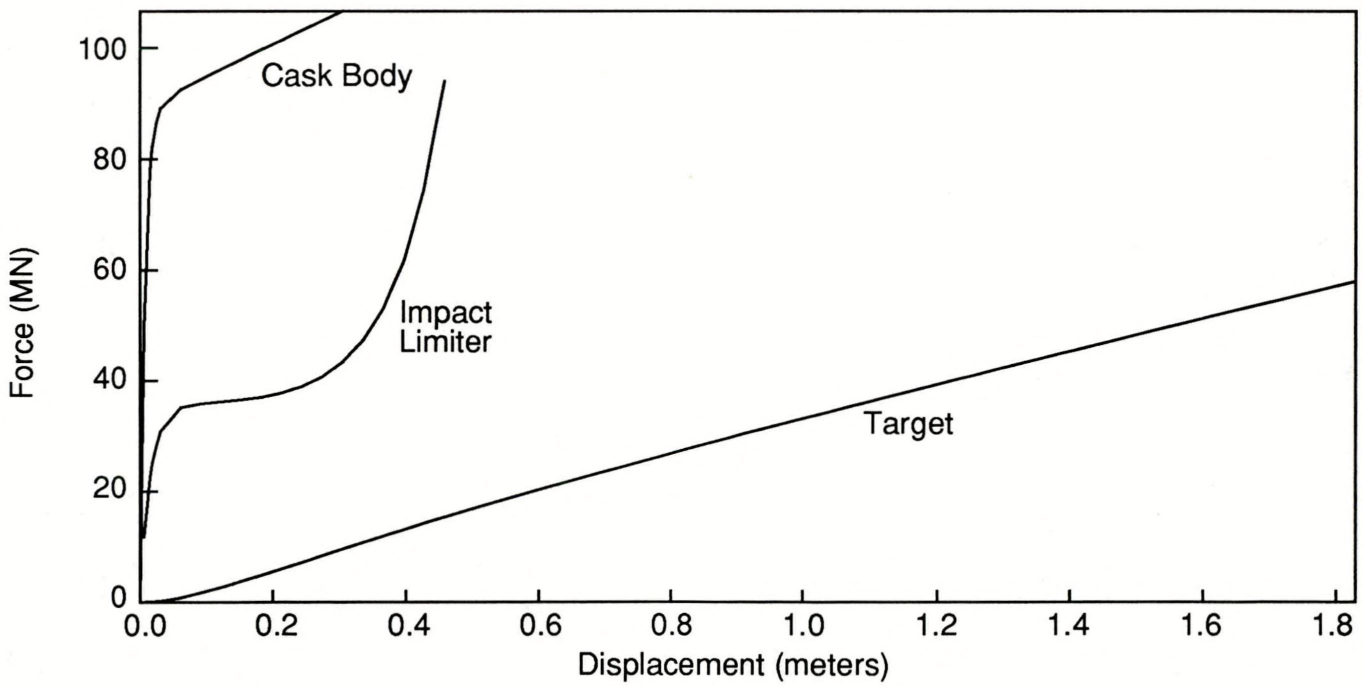

Figure 2 - Force-displacement curves for the springs in the example problem.

impact limiter for this cask is designed using simplified relationships to limit the deceleration from the regulatory drop to 40 g with a crush of 0.23 m, which is below the lock-up deflection of the impact limiting material. This impact limiter is within the normal range used for this type of package, but it is softer than most. In the regulatory 9 meter drop the cask has an actual acceleration of 43.5 g and there is 0.236 m of crush in the impact limiter. The force deflection curve for the impact limiter is shown in Figure 2, along with force deflection curves for the cask body and the hard soil target. For this case the force displacement relationship for the cask body is:

$$F_c = A(1 - e^{-Bx_c} + Cx_c) \quad \text{(EQ 8)}$$

the force displacement relationship for the impact limiter is given by:

$$F_l = D[1 - e^{-Ex_l} + F(e^{G(x_l - H)} - e^{-GH})] \quad \text{(EQ 9)}$$

and the force displacement curve for the hard soil target is given by:

$$F_t = K[JLx_t^{L-1} - P(e^{-Px_t} - e^{-Nx_t})] \quad \text{(EQ 10)}$$

In these equations A-P are constants that define the curves with the values listed below, x_c, x_l, and x_t are expressed in meters and the forces F_c, F_l, and F_t are expressed in Newtons:

A = 89.0 x 10^6 N
B = 131 m^{-1}
C = 0.656 m^{-1}
D = 35.6 x 10^6 N
E = 98.4 m^{-1}
F = 0.1
G = 13.12 m^{-1}
H = 0.244 m
J = 9.81 $m^{-1.922}$
K = 1.76 x 10^6 N.m
L = 1.922
N = 9.84 m^{-1}
P = 4.92 m^{-1}

These equations were developed by fitting experimental and analytical data. It would also be possible to use experimental data directly and express the relationships between force and displacement in tabular form. This method will require numerical integration of the force-displacement curves to calculate the strain energy associated with each spring. For the equations above it is possible to integrate explicitly, resulting in the expressions below for strain energy.

$$E_c = \int_0^{\delta_c} F_c dx_c = A\left[\delta_c + \frac{1}{B}e^{-B\delta_c} - \frac{1}{B} + \frac{C}{2}\delta_c^2\right] \quad \text{(EQ 11)}$$

$$E_l = \int_0^{\delta_l} F_l dx_l$$

$$= D\left[\delta_l + \frac{1}{E}(e^{-E\delta_l} - 1) + \frac{F}{G}e^{-GH}(e^{G\delta_l} - 1 - G\delta_l)\right] \quad \text{(EQ 12)}$$

$$E_t = \int_0^{\delta_t} F_t dx_t = K\left[J\delta_t^L + e^{-P\delta_t} - 1 - \frac{P}{N}(e^{-N\delta_t} - 1)\right] \quad \text{(EQ 13)}$$

The sum of the strain energies for the three springs must be equal to the kinetic energy at impact, which is equal to $1/2MV_1^2$, where V_1 is equal to 26.8 m/s and M is equal to 90,700 kg. This gives a value for the kinetic energy of 32.6 x 10^6 N·m. To determine how this energy is distributed between the cask body, the impact limiter, and the target a complex system of non-linear equations must be solved. Generally for problems of this nature it is easier to solve them numerically with the aid of a computer, but it is possible to use a trial and error method for the solution. One method of doing this is described in the following paragraph.

The first step in the solution is to estimate a force level for the three springs. From this force level and the force-displacement graphs (Figure 2) it is possible to approximate the displacement in each spring. Using these displacements the strain energy in each spring can be calculated by equations 11-13. If the sum of the strain energies is greater than the kinetic energy, then the force level selected is too large; if the sum is less than the kinetic energy, the force level is too small. When the sum of strain energies is approximately equal to the kinetic energy it may be desirable to have a more accurate technique for determining the displacements for a given force level than is possible graphically. At this point equations 8-10 can be used directly, with iterations being performed for each force level to determine the displacement for each spring.

In this example of a 26.8 m/s impact onto a hard soil target, the strain energy in the cask body is 0.09 x 10^6 N·m, the strain energy in the impact limiter is 8.69 x 10^6 N·m, and the strain energy in the target is 23.82 x 10^6 N·m. The force acting on the three springs is 39.4 x 10^6 N. The elastic displacement of the cask body spring is 4.4 mm, the displacement of the impact limiter spring is 0.252 m, and the displacement of the target spring is 1.20 m. The sum of the energy in the cask and impact limiter springs is 8.78 x 10^6 N·m, which is the kinetic energy for a 13.9 m/s impact onto an unyielding target.

If we consider a 26.8 m/s impact of this cask onto the yielding target without its impact limiter the force in the cask and target springs is 45.5 x 10^6 N, the strain energy in the cask body spring is 0.14 x 10^6 N·m, and the strain energy in the target spring is 32.5 x 10^6 N·m. The elastic displacement of the cask body spring is 5.4 mm and the displacement of the target spring is 1.41 m. The equivalent velocity for an impact onto an unyielding target is 1.74 m/s (3.9 MPH). In the two cases the damage to the cask body is likely to be very small or non-existent. This is indicated by the lack of inelastic deformation in the cask body springs. (Note from Figure 2 that a force of 45.5 x 10^6 N is still well within the linear portion of the force-displacement curve for the cask body spring.)

This example demonstrates an important fact concerning target hardness. A target that is hard for one package may be soft for another package. The package system with an impact limiter is not as stiff as the package without the impact limiter. In the case of the package with the impact limiter a significant amount of the impact energy is absorbed by the impact limiter, which is only slightly stiffer than the target for this level of loading. For the package without an impact limiter almost all of the impact energy is absorbed by the target because the cask body is much stiffer than the target.

APPLICATIONS OF METHOD

The example problem defined above described one application for the method described in this paper. For the method to be of merit it must be generally applicable and easy to use. One of the difficulties with the method is determining the force-displacement relationships required to compute strain energies. The equations used in the example problem are of a form that is very typical for cask bodies, impact limiters, and yielding targets. In equation 8, which describes the force-displacement relationship for the cask body, A is the force required to reach yield, the value of B determines the displacement at yield, and the value of C determines the slope of the strain hardening portion of the force-displacement curve. If δ_{yc} is the displacement at yield of the cask body, the value of B can be determined by:

$$B = -\frac{\ln(C\delta_{yc})}{\delta_{yc}} \qquad \text{(EQ 14)}$$

and the value of C can be determined by:

$$C = \frac{\text{strain hardening slope}}{A} \qquad \text{(EQ 15)}$$

In equation 9, which describes the force-displacement relationship for the impact limiter, D is the crush force for the impact limiter, the value of E determines the displacement at the start of the crush plateau, the value of F determines the slope of the crush plateau, the value of G determines how steeply the lock-up portion of the force-displacement curve rises, and H is the displacement at the start of lock-up. Because of the complexity of equation 9, it is difficult to develop equations for determining constants E, F, and G, but the discussion above provides guidelines for determining the appropriate values for these constants.

The determination of the force-displacement relationship for yielding targets is more difficult. Equation 10 was developed by curve fitting of experimental data for impacts onto hard native desert soil in the vicinity of Albuquerque[4,5]. These tests had displacements ranging from 0.5 to 2.5 meters. A close approximation to the curve described by equation 10 can be made with a straight-line fit of the experimental data. The equation for this line is:

$$F_t = Qx_t \qquad \text{(EQ 16)}$$

where Q is the linear stiffness of the target, and in the example is equal to 31.71 x 10^6 N/m.

Many targets can be approximated with a linear force-displacement curve, but a notable exception is a concrete highway surface. In this case a large force is required to form a shear plug in the concrete. After this shear plug is formed the surface is much weaker, and can be approximated by a linear force-displacement curve. Analyzing impacts onto this type of target requires a slightly different approach. If the force from the impact is not sufficient to generate the shear plug the target can be modeled as a linear spring with relatively high stiffness. This case is similar to the method discussed previously. If the force from the impact is large enough to generate the shear plug the impact can be considered as two events. In the first event the impact is with the undeformed concrete target. This event ends with the formation of the shear plug. The energy required to produce the shear plug is subtracted from the initial kinetic energy to determine the kinetic energy for the second event. From this point the analysis proceeds in a manner similar to that described in the preceding example. This method was successfully used to compare the results of tests on concrete targets for a package without impact limiters[4].

LIMITATIONS

To apply the method for relating impacts with yielding targets to impacts with an unyielding target described in this paper the user must know the load-displacement properties of the target as well as the cask body and impact limiter. For most radioactive material shipping packages the cask body is much more rigid than the impact limiter, and a close approximation to the solution can be obtained by assuming the cask is rigid. This reduces the spring system to two springs: one representing the impact limiter and one representing the target. For many targets, such as vehicles and posts, the amount of energy they can absorb before failing is finite. In these cases, if the impact energy is greater than the energy absorbed by the cask body, impact limiter, and target at the time the target fails, the package will not be stopped by the impact and will have a residual kinetic energy.

The modelling of the cask body, impact limiter, and target as springs implies that the impact event is one-dimensional. That is, there is no load transmitted normal to the direction of motion. For packages such as the one in the example, where the cask body is much stiffer than the impact limiter, loads at this interface that are normal to the direction of motion have little significance and the one dimensional crush is an accurate approximation. At the interface between the impact limiter and the target it is quite likely that loads in the transverse direction will cause crushing of either the impact limiter or the target, which will result in some energy absorption. This fact will tend to reduce the severity of the impact on the yielding target compared to the impact modelled as one dimensional crush. Severe impact tests on small packages conducted by Bonzon[3] showed this result in differences in failure mode. Impacts onto soil targets that had deformations of the cask body similar to lower velocity impacts onto an unyielding target did not result in gross failure of the containment boundary, while the impacts on the unyielding target did. The change in failure mode caused by transverse forces is impossible to model as an impact onto an unyielding target at a lower velocity. The method of this paper will consider the impact onto the yielding target to be more severe than it actually is. For the purpose of risk assessments or hazard communications this result is conservative.

CONCLUSIONS

A mathematically rigorous method is developed for relating impacts with yielding targets to lower velocity impacts with unyielding targets. The method correctly models the mechanics of the impact and the conversion of kinetic energy to strain energy. An important result shown by the example problem is that target hardness depends on the stiffness of the impacting package. For a cask with impact limiters a 26.8 m/s impact onto hard soil is equivalent to a 13.9 m/s impact onto an unyielding target. For the same cask without the impact limiters a 26.8 m/s impact onto hard soil is equivalent to a 1.74 m/s impact onto an unyielding target. This is one reason why non-technical members of the public have a hard time realizing the severity of the regulatory impact. For most people, objects such as trucks and bridge columns appear to be very hard, but to many radioactive material shipping packages these objects are relatively soft.

The method for relating impacts with yielding targets to lower velocity impacts with unyielding targets discussed in this paper helps to explain how the regulatory impact accident provides a high degree of safety to the public. This methodology is relatively simple to use, and can be applied to the "What if" scenarios brought up by interveners.

ACKNOWLEDGEMENTS

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