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IMPACT ANALYSIS OF CASKS - A SIMPLIFIED METHOD

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Introduction :

Transportation of radioactive materials poses a potential health hazard due to the possibility of radioactive spillage. IAEA has several guidelines for the design and testing of such packages to survive normal and accident conditions of transport. One of the regulatory requirements of the IAEA is that the cask must survive a 9-metre drop onto an unyielding target in an orientation causing maximum damage, without any radioctivity release.

Two of the orientations usually studied are the a) End Drop and b) 'Centre of Gravity over Corner' Drop. The End Drop Case yields large decelerations, large impact forces and small impact durations. The 'CG over Corner' case, because of plastification of the Corner, yields small decelerations, small impact forces and large impact durations.

Two simplified computer codes, one static and another dynamic have been developed for the solution of such impact problems. This paper describes these codes CASK-STATIC and CASK-DYNAMIC, and compares their results with a standard NAFEMS (National Agency for Finite Element Methods and Standards) benchmark problem [1].

In the case of 'End Drop', CASK-STATIC results are compared with the published NAFEMS finite element results. In this problem as suggested by NAFEMS, a 32.4 mm long, 3.2 mm radius copper rod impacts a rigid barrier in a normal end-on configuration with a velocity of 227 m/s. NAFEMS results show the characteristic elephant-foot deformed shape (fig.1). The final lenghts of the copper rod as obtained from the static code and the benchmark problem are compared.

For the 'CG over Corner' configuration, the CASK-STATIC and CASK-DYNAMIC Codes are compared with each other. Here again the same copper rod is considered, but impacting a rigid barrier at an angle of 11.17 degrees from the vertical. This configuration ensures that translational energy is not converted into rotational energy. Thus all the energy is dissipated in plastic deformation. The impact velocity is taken to be equal to that of a 9m drop (13 m/s).

For an oblique drop where the CG does not lie over the point of impact, CASK-STATIC and CASK-DYNAMIC are compared for a 20 degree angled drop using the same copper rod.

CASK-STATIC :

During the impact of the cask with an unyielding target, the energy of drop has to be absorbed in crushing of the cask in the impact zone. The static code is written for the configuration of the cask when the downward velocity of the cask has reduced to zero, the deceleration is maximum and the kinetic energy of the cask has been completely absorbed in crushing the cask base and deforming the cask shell. The static code uses the energy balance principle in arriving at the crush depth, and the stresses and strains in the cask body [2]. The code has been written for hollow cylindrical and square casks with sacrificial material at the bottom of the cask. The code can account for different liner and shielding materials and can compute decelerations, impact forces and stresses for any orientation of drop.

The code starts off by making an assumption on the depth of crushing of the cask bottom (fig. 2). This may be a cylindrical or cubic shape for an end impact, or a ungula or tetrahedral shape for a corner impact, for cylindrical and square base casks respectively. Different liner and shielding materials are taken into account. The energy absorbed in crushing is obtained from the formula :

$$E = \sigma_{cr} \times V_{cr}$$

where

E = Energy absorbed in crushing
σ_{cr} = Crushing stress
V_{cr} = Crushed volume

The impact force transmitted to the shell is obtained from

$$F_{cr} = \sigma_{cr} \times A_{cr}$$

where

F_{cr} = Crushing force
A_{cr} = Crushed area

The strain energy absorbed in the shell is calculated as follows. The cask length is divided into 100 sublenghts. On any one of these sublenghts of the cask body, an external moment and a normal compressive force will act. This external moment and normal force is assumed to remain constant over this sublength. This can be obtained from the crushing force, the angle of inclination of the cask and the inertia forces acting on the cask CG. The inertial accelerations are obtained from the impact force and the cask mass, both translational and rotational. The external normal force and the bending moment at each cask section is then equilibriated with a constant and a linearly varying stress distribution. Due to the possibility of plastification, a layered iterative technique is used (fig. 3). In this technique a section is divided into a number of layers. A constant and a linearly varying strain distribution is assumed over the cross section. The internal moment and normal force is calculated from these strains by summation over all the layers. This is then compared with external values. As initially a large strain was assumed, this internal force and moment will be larger than the external values. These are then iteratively reduced till a balance is obtained. To account for plasticity of the shield and liner materials, bilinear stress vs. strain curves are used. At this stage the strain energy for this sublength is calculated. This procedure is repeated for all the 100 sublenghts, and a sum of the strain energies for the shell is found.

The sum of the strain energies in the crushed end and the cask shell will in general be less than energy of drop as a small initial depth of crush was assumed. An external iterative procedure is used in which the depth of crush is modified to get a energy balance.

For orientations where the CG does not lie vertically above the point of impact, due to the transformation of translational kinetic energy to rotational kinetic energy, complete energy of drop is not converted into strain energy. This is handled by assuming that the potential energy of the cask is given by [3].

$$U_p = W_t \times H$$

where W_t = translational weight and H = drop height. Translational weight W_t is a fraction of the total weight W_T, and is given by :

$$W_t = \left[\frac{W_T\, d^2 + I_y\, g}{W_T\, p^2 + I_y\, g} \right] W_T$$

where, p is distance between impact point and the CG, d is the height of the CG above the impact surface, and g is the gravitational acceleration.

Comparison Between CASK-STATIC & NAFEMS FEM solution :

A 32.4 mm long, 3.2 mm radius copper rod impacts normally on a rigid barrier with a velocity of 227 m/s. The copper bar properties are as follows :

σ_y = 400 N/mm^2

$E_{elastic}$ = 117E+03 N/mm^2

$E_{plastic}$ = 0.1E+03 N/mm^2

ρ(Ro) = 8930E-09 kg/mm^2

σ_{cr} = 550 N/mm^2

Final deformed length as reported by NAFEMS : 21.5 mm.
Final deformed length as per CASK-STATIC : 23.5 mm.

CASK-DYNAMIC :

This computer code models the complete impact phenomenon from the time the cask bottom first touches the rigid surface, upto the time the cask starts to rebound [4]. This is specially useful when the cask does not fall in the 'End Drop' or the 'CG over Corner' configuration and considerable rotation of the cask CG along with sliding at the cask base is expected. This gives more accurate results as compared to the 'Translational Mass' method described under CASK-STATIC.

CASK-DYNAMIC assumes that the cask body is rigid, and that energy absorption takes place only by crushing of the cask base. This is a reasonable assumption as most of the energy actually gets absorbed by crushing.

The three equations of motion are :

$$\frac{W}{g} * \frac{\partial^2 u}{\partial t^2} = -F_v + W \qquad .. (1)$$

$$\frac{W}{g} * \frac{\partial^2 w}{\partial t^2} = F_h \qquad .. (2)$$

$$J * \frac{\partial^2 ⌠}{\partial t^2} = F_v \times X_v - F_h \times X_h \qquad .. (3)$$

where

u, w, ⌠ are the vertical, horizontal and rotational components of displacement of cask CG.
g = gravitational constant
F_v = Vertical component of impact force acting on the point of impact.
F_h = Horizontal component of impact force acting on the point of impact.
X_v = Distance of F_v from CG
X_h = Distance of F_h from CG

Initial condition is given as a vertical downward velocity. The code monitors the horizontal, vertical and rotational components of displacements, velocities and accelerations as the impact proceeds. For every load step, from the downward deflection of the CG and the current rotation angle, the new crushed depth for the cask corner is calculated. From this the impact forces are found. The same method as used for the static code is employed. That is, from the crushed depth, the crushed volume and crushed area are evaluated, from which the strain energy absorbed and the impact force is found. From the forces, the accelerations can be found by dividing by the corresponding masses. The velocities and displacements are found by solving the three equations of motion (three simultaneous non-linear ordinary differential equations) using the Runge-Kutta 4th order solution algorithm. The cask bottom will start sliding when the frictional force is not sufficient to keep the cask base stationary. The computation is terminated when the cask starts to rebound.

Comparison between CASK-STATIC and CASK-DYNAMIC :

A 32.4 mm long, 3.2 mm radius copper rod impacts obliquely on a rigid barrier with a velocity of 13.3 m/s.

a) CG over corner :
The obliquity is 11.17 degrees from the vertical. This produces the 'CG over corner' drop orientation. The copper bar properties are same as given previously.

Final crush depth from CASK-STATIC : 0.40 mm.
Final crush depth from CASK-DYNAMIC : 0.41 mm.

b) Drop angle = 20 degrees :

Final crush depth from CASK-STATIC : 0.57 mm.
Final crush depth from CASK-DYNAMIC : 0.56 mm.
Orientation before rebounce, from CASK-DYNAMIC : 20.5 degrees.

Conclusions :

From the comparisons given above, it is seen that there is a good agreement in results between the FEM Benchmark and CASK-STATIC for the 'End Drop', and between CASK-STATIC and CAK-DYNAMIC for the 'Corner drops'. This indicates that the simplified codes developed by the authors can be used as a good starting point for the analysis of such impact problems. Once a critical drop orientation is identified, a detailed FEM analysis may be performed. This would save time and computational effort.

References :

[1] NAFEMS-BENCHMARK : "A Simple Benchmark for Impact" - July 1990.

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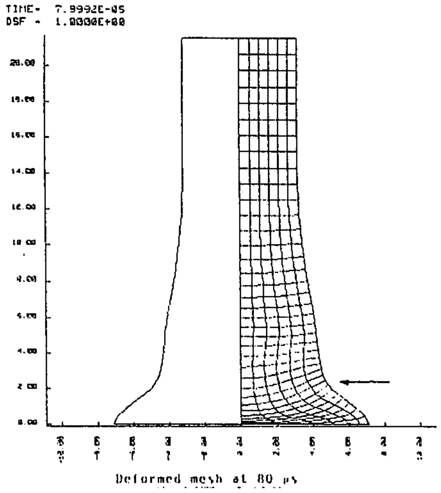
[3] G. Szuladzinski - "Dynamics of Structures and Machinery (John Wiley and Sons, Inc., 1982) pp.158-167.

[4] C.A. Miller & C.J. Constantino - "Impact Loading on Waste Fuel Shipping Casks" - Transactions of the 9th International Conference on 'Structural Mechanics in Reactor Technology', Vol. J.

Fig 1



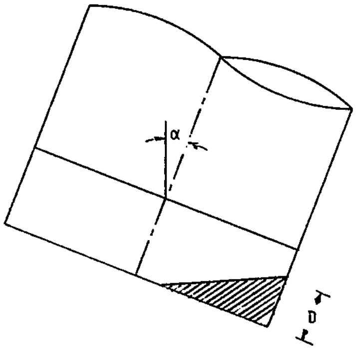


FIG.2 OBLIQUE ANGLE CRUSHING OF CASK BOTTOM SHOWING DEPTH OF CRUSH

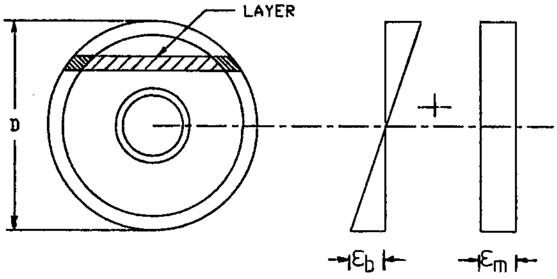


FIG. 3 CROSS SECTION SHOWING A TYPICAL LAYER AND THE ASSUMED STRAIN FIELD.