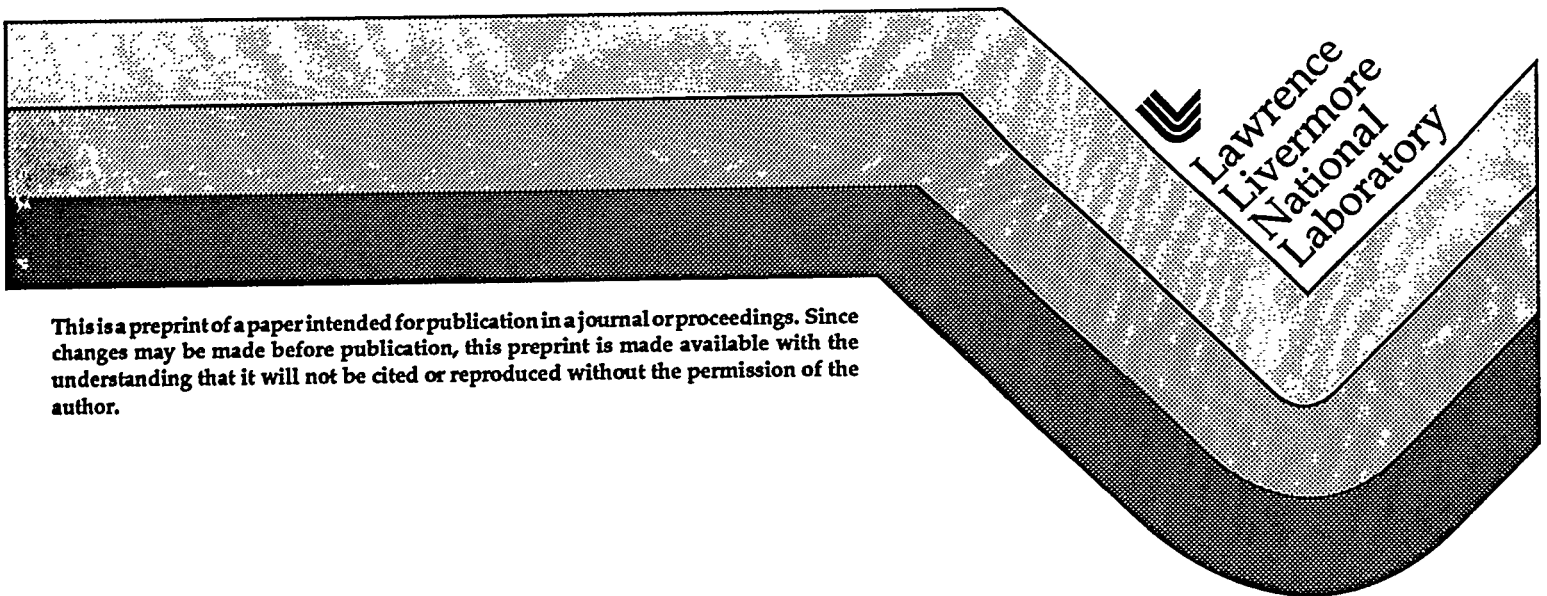


**Casks (Computer Analysis of Storage Casks)
A Microcomputer Based Analysis System
for Storage Cask Review**

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CASKS (COMPUTER ANALYSIS OF STORAGE CASKS)
A Microcomputer Based Analysis System for Storage Cask Review

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MASTER

CASKS (COMPUTER ANALYSIS OF STORAGE CASKS)*
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ABSTRACT

CASKS is a microcomputer based computer system developed by LLNL to assist the Nuclear Regulatory Commission in performing confirmatory analyses for licensing review of radioactive-material storage cask designs. The analysis programs of the CASKS computer system consist of four modules—the impact analysis module, the thermal analysis module, the thermally-induced stress analysis module, and the pressure-induced stress analysis module. CASKS uses a series of menus to coordinate input programs, cask analysis programs, output programs, data archive programs and databases, so the user is able to run the system in an interactive environment. This paper outlines the theoretical background on the impact analysis module and the yielding surface formulation. The close agreement between the CASKS analytical predictions and the results obtained from the two storage casks drop tests performed by SNL and by BNFL at Winfrith serves as the validation of the CASKS impact analysis module.

INTRODUCTION

The U.S. Nuclear Regulatory Commission requested the Lawrence Livermore National Laboratory to develop an integrated software system to conduct confirmatory analyses of the

shipping casks. The purpose of the analyses was to ensure structural integrity under a series of normal operating loads and hypothetical accident loads as specified in Title 10 of the *Code of Federal Regulations* (10 CFR 71, 1983). As a result, SCANS was produced by LLNL in 1988 (Gerhard, 1988).

SCANS is a microcomputer based system of computer programs for evaluating safety analysis reports on spent fuel shipping casks. The system is easy to use and provides an independent check for reviews on the analyses submitted by licensees. SCANS calculates the global response of the shipping casks to impact loads, thermal conditions and pressure loads.

In 1989, the U.S. Nuclear Regulatory Commission again requested LLNL to develop a microcomputer based computer program for evaluating the safety analysis reports on spent fuel storage casks based on the SCANS code. Due to the similar nature of structural designs between the two casks, we employed the existing framework used in the SCANS program and made a number of enhancements and modifications in the impact analysis module to accommodate requirements unique to storage casks. These include: the variable drop height, the variable drop angle, and the option to accommodate

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storage cask impact on a yielding surface. The modified program is named CASKS (Chen, 1995).

Structured the same way as SCANS, CASKS is composed of a series of menus, input programs, cask analysis programs and output display programs. An analysis is performed by preparing the necessary input data and then selecting the appropriate analysis: impact, thermal (heat transfer), thermally-induced stress, or pressure-induced stress. All data is entered through fill-in-the-blank input screens with descriptive data requests. Where possible, default values are provided. The input data is evaluated for correctness before it is accepted.

CASKS allows the user to analyze cask impact on either an unyielding or a yielding surface. A yielding surface is represented as a series of nonlinear force-deflection relationships. To analyze yielding surface cask impact, CASKS first combines the surface force-deflection relationship with the force-deflection relationship of the cask 'impact limiter' prior to the analysis.

Most of the storage casks do not require impact limiters. However, CASKS code requires the user to specify an impact limiter force-deflection curve before the code can be executed, even when there are no physical impact limiters on the cask. This requirement can be thought of as the relative 'stiffness' or 'flexibility' of the part of the cask that contacts the target on impact. The 'stiffness' of the cask is derived by entering a 'pseudo' force-deflection curve for the cask.

Based on the general geometry description, CASKS automatically generates appropriate two-dimensional finite-element meshes for thermal, thermal-stress, and pressure-stress analyses. CASKS allows steady-state or transient thermal analyses, which may include phase change, time and/or temperature-dependent material prop-

erties, time and/or temperature boundary conditions, and internal heat generation. Possible thermal boundary conditions include specified temperature, heat flux, convection, radiation, interface contact resistance, and nonlinear heat transfer to a bulk node. Thermal analyses use 4-node elements. Thermal-stress and pressure-stress analyses are performed using a linear-elastic static structural analysis program which allows temperature-dependent material properties. Stress analyses use 9-node elements.

Users can choose to display or print the graphical output. Graphic displays include: impact force, moment and shear time histories; impact animation; thermal/stress geometry outline; thermal/stress element outlines; temperature distributions as iso-contours or profiles; and temperature time histories.

This paper discusses the CASKS impact analysis formulation together with the yielding surface representation specifically related to the storage casks.

CASKS IMPACT THEORETICAL BACKGROUND

Cask impact analyses use a one-dimensional dynamic beam model. Each node in the beam model has two translational degrees of freedom and one rotational degree of freedom. The impact code uses an explicit time-history integration scheme in which equilibrium is formulated in terms of the global external forces and internal force resultant. This formulation allows the code to track large rigid-body motion. Thus, CASKS can calculate the oblique impact problem from initial impact through essentially rigid-body rotation to secondary impact.

Equation of Motion

In oblique drops of casks, the equation of motion which is capable of handling large rigid body rotations can be written as:

$$[M] \{\ddot{X}\} = \{F\} - \{P\} \quad (1)$$

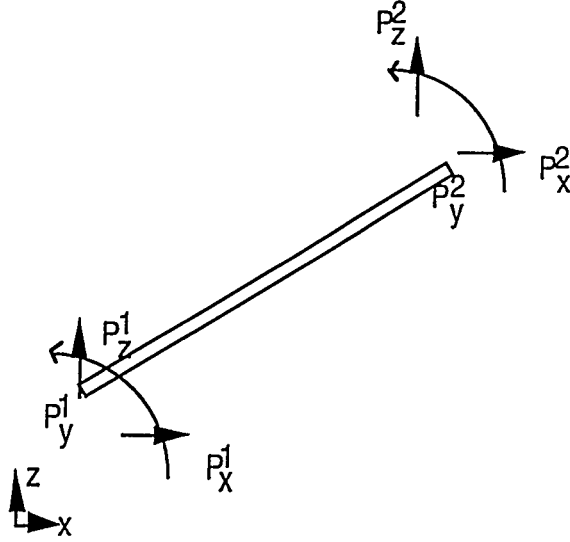


Figure 1. Beam element forces in global coordinates

where $\{P\}$ represents the internal force vector on the beam elements, acting on the nodal points. A typical element-level internal force vector $\{P\}$ has six components, three at each end of the beam element (see Fig. 1):

$$\{P\} = \begin{Bmatrix} P_x^1 \\ P_y^1 \\ P_z^1 \\ P_x^2 \\ P_y^2 \\ P_z^2 \end{Bmatrix} \quad (2)$$

The external force vector $\{F\}$ comprises the body weights of the cask and its contents as well as the impact forces during impact. The magnitude of $\{F\}$ is

determined from the force-deflection curves of the impact limiters. As stated, a 'pseudo' force-deflection curve is needed when no physical impact limiter is presented in a cask.

The equation of motion (1) is solved with the method of central difference. Equation (1) is rewritten as

$$\{\ddot{X}_n\} = [M]^{-1} \{F_n - P_n\} \quad (3)$$

where the subscript refers to a point in time. Knowing $\{F_n\}$, $\{P_n\}$, and $\{X_{n-(1/2)}\}$, we can integrate Eq. (3) in the following manner:

$$\{\dot{X}_{n+(1/2)}\} = \{\dot{X}_{n-(1/2)}\} + (\Delta t) \{\ddot{X}_n\}$$

Thus,

$$\{\dot{X}_{n+(1/2)}\} = \{\dot{X}_{n-(1/2)}\} + (\Delta t) [M]^{-1} \{F_n - P_n\} \quad (4)$$

$$\{X_{n+1}\} = \{X_n\} + (\Delta t) \{\dot{X}_{n+(1/2)}\}$$

Knowing $\{X_{n+1}\}$, we can calculate $\{F_{n+1}\}$ from the force-deflection curves of the impact limiters, and then use Eq. (2) to calculate the internal force vector, $\{P_{n+1}\}$. The numerical integration requires the use of $\{\dot{X}_{-(1/2)}\}$ for the first cycle of computation:

$$\begin{aligned} \{\dot{X}_{-(1/2)}\} &= \{\dot{X}_0\} - (1/2) (\Delta t) \{\ddot{X}_0\} \\ &= \{\dot{X}_0\} - (1/2) (\Delta t) [M]^{-1} \{F_0\} \end{aligned} \quad (5)$$

The explicit time integration is stable only if

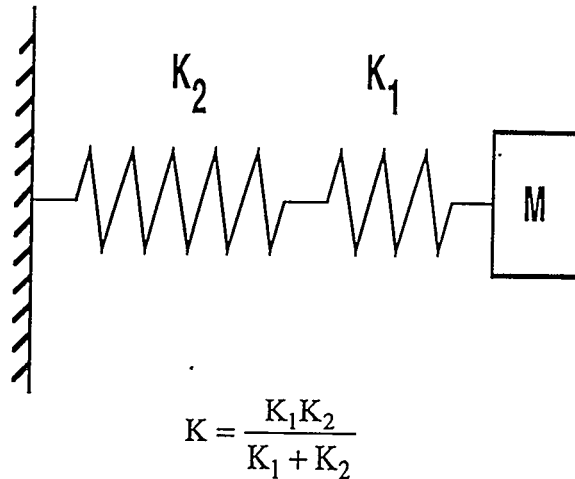
$$(\Delta t) \leq T_{\min} / \pi = 2 / \omega_{\max} \quad (6)$$

where $T_{\min}$ is the smallest period of the finite element assemblage, and $\omega_{\max}$ is the maximum frequency in radians per second.

Yielding Surface Representation

The yielding surface application is unique to the spent fuel storage cask. This is because storage casks are normally moved only from the fuel handling building to the storage pad at the site of a reactor. Typically, the hardest surface that a storage cask could fall onto is a concrete pad. Any roadway or other surface that a cask would pass over is less rigid. Consequently, storage casks can be evaluated assuming that the impact is on the reinforced concrete pad. This contrasts with shipping casks which are usually transported over a long distance and may fall onto different types of surfaces in an accident. Therefore, an unyielding impact surface must be assumed to insure that any real accident will involve an impact with a less rigid surface.

Most cask storage sites in the U.S. are constructed by placing a reinforced concrete slab on compacted soil subgrade. Storage casks are then placed directly on top of the concrete slab for at-site interim storage. Therefore, the formulation of the yielding surface model should consider both the concrete slabs and the soil subgrade. The complexity of the formulation should be compatible with the existing CASKS code, allowing it to be readily implemented into the code. Toward this end, a force-deflection relationship of the yielding surface was sought which resembles the force-deflection relationship of impact limiters on the casks. The force-deflection curve of the yielding surface can then be readily combined with that of cask 'impact limiter' to form an equivalent or composite F/D curve. The scheme is depicted in Figure 2.



where

K_1 = cask impact limiter (or pseudo) stiffness,

K_2 = foundation stiffness, and

K = equivalent or composite stiffness.

Figure 2. Equivalent or composite force-deflection relationship of a storage cask

CASKS MENU STRUCTURE

CASKS uses a series of menus to coordinate input programs, cask analysis programs, output programs, data archive programs and databases. Figure 3 illustrates the menu structure. The menus are ordered according to the stages of an analysis. CASKS requires only the press of a single key to make menu and subtask selections. CASKS indicates the available selections on each display screen and describes what action CASKS will take. For example, on the main menu CASKS indicates the appropriate keys to press are 1 2 3 4 5 6 and Q; the action taken after pressing key Q is to return to DOS. A typical menu screen of CASKS program is shown in Figure 4. The Main Menu is the central hub of CASKS. It provides access to five task menus and the select cask facility. The task menus are connected only through the Main Menu. They cannot call each other directly.

Data is entered through fill-in-the-blank input screens. Full editing features are available (insert, delete, move cursor, overtype, etc.), and data items are accepted when the cursor is moved to another data field.

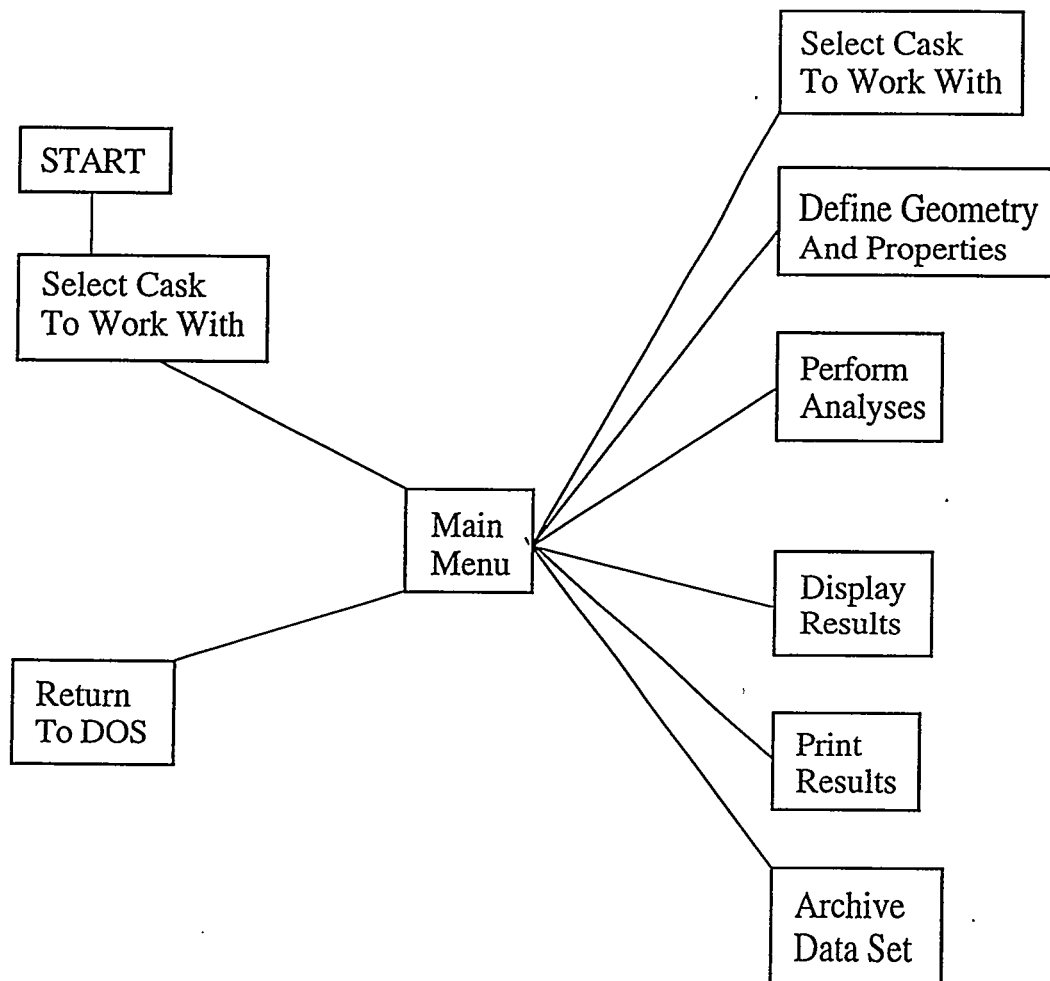


Figure 3. CASKS menu structure.

CASKS is designed for microcomputers compatible with the IBM-PC family of computers.

The minimum required hardware configuration is:

IBM "XT" or "Compatible" with the following:

10 Mbyte hard disk drive

360 Kbyte floppy disk

640 Kbyte RAM

CGA Board (Color Graphics Adapter)

Color Graphics Monitor

8087 Math co-processor chip

IBM or EPSON Graphics printer

CASKS performance is improved by using turbo XTs, ATs, IBM PS2s, 80X86 class of machines, and compatibles.

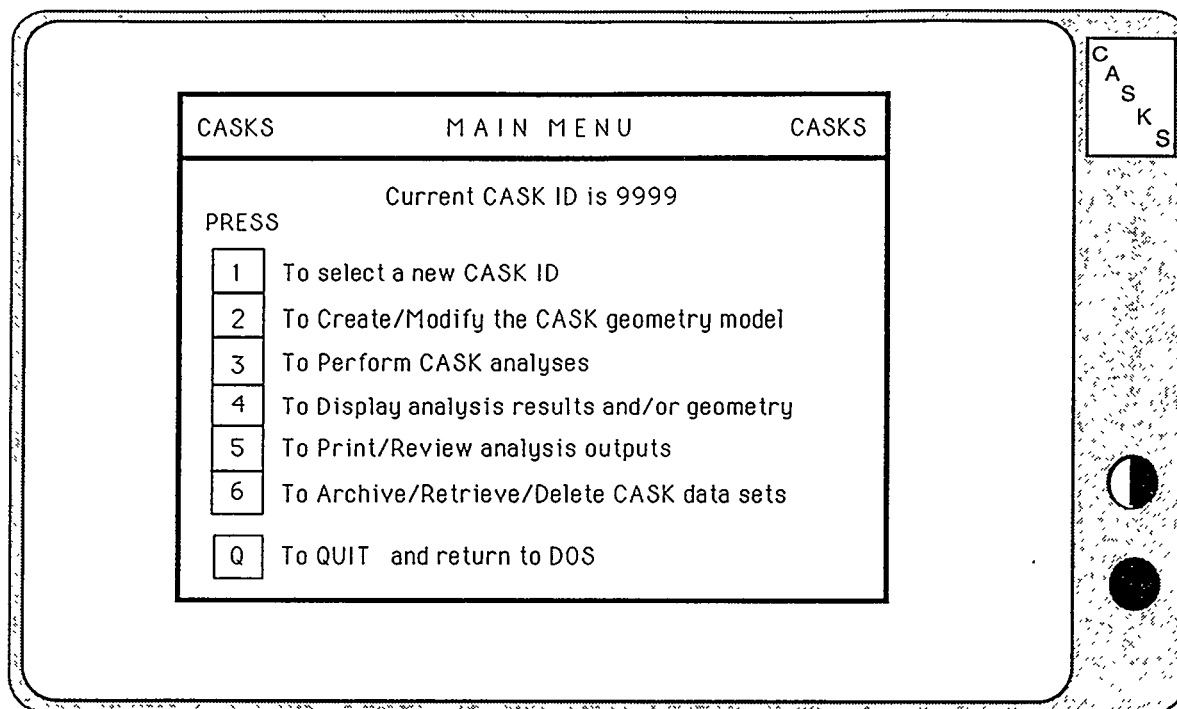


Figure 4. CASKS Main Menu.

BENCHMARKING OF CASKS CODES

Two cask drop tests were selected for the validation of the CASKS code with a yielding surface option by comparing the code prediction with experimental data. These are drop tests performed at Sandia National Laboratories (SNL) and at British Nuclear Fuels Limited (BNFL) facility in Weinfrith, England.

Steel Billet Drop Test at SNL

In March of 1993, Lawrence Livermore National Laboratory designed a series of drop tests of an instrumented steel billet for the Storage Division of the Office of Nuclear Materials Safety and Safeguards of NRC. These series of tests were carried out at Sandia's cask drop site (Hovingh, 1995). A sequence of five tests were performed to study the effect of a concrete pad design with various soil subgrades on the deceleration forces on a steel billet. The steel billet is 20 in. in

diameter, 72 in. long, and weights 6600 pounds. No impact limiter was installed on the billet. The pad was constructed in accordance with the specifications and codes of the American Concrete Institute (ACI 318). The compressive strength of the concrete pad (f_c) is 3000 psi. The dimensions of the concrete pad are 72 in. square x 12 in. thick. The reinforcing steel bars used are #3 bar (0.375-in. diameter) with 18-in. center. Steel reinforcing bars are laid 1 in. below the surface of the pad. Yield stress of the steel bar is 60 ksi. The billet drop height was 18 in. (impact velocity of 9.8 ft/s) in all the tests. The test condition simulates an accidental drop scenario of a scaled model of a storage cask onto its supporting pad.

As mentioned in the Introduction, CASKS code requires the user to specify the impact limiter force-deflection curve before the code can be executed, even when there was no physical impact limiter presented on the cask. It is possible to estimate this stiffness value by employing

a dynamic finite element analysis of the contact region of the cask to the target on impact, using appropriate cask material properties. However, since this series of billet impact tests included a test (Test #166) in which the steel billet was dropped onto an unyielding foundation, thus it provides a simpler means than using the finite element analysis to derive the approximate cask stiffness. This is accomplished by selecting an initial stiffness and then subjecting the steel billet to an impact onto an unyielding target in CASKS code. The maximum deceleration produced in the steel billet, as predicted by the code, is then compared to the test result obtained from the steel billet drop onto an unyielding surface obtained from Test #166. Subsequent adjustments to the initial stiffness are made until maximum deceleration predicted by the CASKS code is close to that of the test result.

The billet drop test onto an unyielding target (#166) recorded a maximum deceleration of 250 g using a 500 Hz filter. CASKS produced a maximum deceleration of 281.3 g when a stiffness of 15,000 kips/in. was used for the cask 'impact limiter' force-deflection curve. Therefore, the 'stiffness' of the cask* is determined to be 15,000 kips/in.

Next, employing the method recommended by Salveson & Romstad (Salveson, 1993), the force-deflection pairs of the yielding surface can be estimated. The yielding surface force-deflection pairs were then entered into the CASKS system.

* In a more stricter sense, there are actually two parts that make up the 'stiffness' of cask: the flexibility of the part of the cask that contact the theoretical unyielding surface, and the flexibility of the 'unyielding surface' where the test was conducted. Since it is difficult as well as unnecessary to quantify the contribution from each part, two parts are simply lumped together as the 'stiffness' of the cask.

While keeping the same cask 'impact limiter' stiffness (15,000 kips/in.) as described earlier, a dynamic-impact analysis of the steel billet end drop of 18 in. was performed. CASKS predicted a maximum deceleration in the billet to be 133.6 g. Accelerometers mounted on the billet showed the maximum deceleration on the billet during the drop test was 93 g to 140 g using a 500 Hz filter. Therefore, CASKS predicts a comparable maximum billet impact deceleration to that of the test result.

It is interesting to observe that the peak deceleration produced in the billet as predicted by CASKS for impact onto an unyielding surface (281.3 g) is more than twice the peak deceleration value (133.6 g) predicted by dropping the billet on a yielding foundation.

Excellox 3A Spent Fuel Transport Cask Drop Test at BNFL

There were four drops performed at Winfrith, UK. using the Excellox 3A spent fuel transport cask. The cask as tested included the lead liner and the storage lid. In addition, a plate fitted into the base recess to assist in spreading the cask load over the entire base area during the drop. The impact limiters and the basket (as well as any contents) were not included in the test (Hovingh, 1995). The cask is 58 in. in diameter, 216 in. long, and weights 141900 pounds. The dimensions of the concrete pad are 216 in. square x 36 in. thick. The reinforcing steel bars used are #10 bar (1.34-in. diameter) with 6.5-in. center. Steel reinforcing bars are laid 3 in. below the surface of the pad. Yield stress of the steel bar is 75 ksi. The cask drop height was 60 in. (test no. 4).

Following the same procedure outlined for the SNL billet drop test, the 'stiffness' of the cask (using test no. 2 result--cask impacting on an essentially unyielding surface) is determined to be 60,000 kips/in, which yields a maximum predicted deceleration of 110.6 g. (The measured peak deceleration was 103 g.)

Next, the yielding surface force-deflection pairs for this case was estimated and were entered into the CASKS system. While keeping the same cask 'impact limiter' stiffness (60,000 kips/in.) as described earlier, a dynamic-impact analysis of the cask end drop of 60 in. was performed. CASKS predicted a maximum deceleration in the cask to be 124 g. Accelerometers mounted on the cask showed the peak deceleration on the cask during the drop test was 118 g using a 350 Hz filter. Thus, again, CASKS predicts a comparable peak cask impact deceleration to that of the test result.

CONCLUSION

CASKS computer system developed by LLNL offers an easy-to-use program in performing confirmatory analysis of storage cask designs. The system is able to handle the cask impact onto either an unyielding surface or a yielding surface. The 'stiffness' of the part of the cask that contacts the target on impact as well as the yielding surface are both represented by a series of non-linear force-deflection pairs. Thus, an accurate estimation of these force deflection pairs are essential to the successful simulation of storage cask drops.

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