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CRUSH: A SIMPLIFIED COMPUTER PROGRAM FOR IMPACT ANALYSIS OF RADIOACTIVE MATERIAL TRANSPORT CASKS

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CRUSH: A Simplified Computer Program for Impact Analysis of Radioactive Material Transport Casks

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In drop impact analyses for radioactive shipping casks, it has become possible to perform them in detail by using interaction evaluation computer programs, such as DYNA2D, DYNA3D, PISCES and HONDO. However, the considerable cost and computer time are necessitated to perform such analyses by these computer programs. Therefore, simplified analysis computer programs which are capable of reducing cost and computer time are needed. To meet the above requirements, simplified computer program CRUSH has been developed. CRUSH is static calculation computer program capable of evaluating the maximum acceleration of the cask body and the maximum deformation of the shock absorber using the Uniaxial Displacement Method (UDM).

In the paper, brief illstration of calculation method using UDM is presented. The second section presents comparisons between UDM and detailed method. The third section provides a user's input guide for CRUSH.

Keywords: Computer Program, Impact Analysis, Cask, Drop Impact, UDM, Structural Analysis, Static Analysis, Shipping Cask

CRUSH：放射性物質輸送容器の衝突簡易計算プログラム

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幾島　毅

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放射性物質輸送容器の落下衝突解析において，DYNA2D，DYNA3D，PISCESおよびHONDOのような詳細計算プログラムを用いて計算できる。しかし，これらの計算プログラムによって計算する場合，多くの計算費用と計算時間が必要である。それ故，計算費用と計算時間を少くするような簡易計算プログラムが必要とされる。このような要請から，簡易計算プログラムCRUSHを開発した。CRUSHは1次元変形法（UDM法）を用いた静的計算プログラムであり，輸送容器本体の最大加速度およびショックアブソーバーの最大変形量を計算するものである。

本報告書はUDM法の説明，UDM法と詳細計算法による計算結果の比較およびCRUSH計算プログラムの取扱いについて述べたものである。

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1. Introduction

In the drop impact analyses for radioactive material shipping casks, it has become possible to perform them in detail using interaction evaluation computer programs, such as DYNA2D, DYNA3D, PISCES and HONDO. However, the considerable cost and calculation time are necessitated to perform such analysis by these computer programs. Therefore, simplified computer programs which are capable of reducing cost and calculation time are needed to perform parameteric survey or sensitivity evaluations in designing a shipping cask and conducting its safety analysis. To meet the above requirements, as show in Fig. 1.1, Japan Atomic Energy Research Institute (JAERI) is now under developing some simplified analysis computer programs.

In the field of the drop impact analysis of shipping casks with shock absorbers, simplified computer programs CRUSH and CASH-II has been developed in JAERI. CRUSH is the static calculation computer programs capable of evaluating the maximum acceleration of cask body and the maximum deformation of the shock absorber using the Uniaxial Displacement Method (UDM) which is an improvement on a conventional theory based on the Volumetric Displacement Method (VDM).

Conventionally, the VDM has been a usual method to evaluate a large three dimensional deformation. In the VDM, the absorption of drop energy is to be evaluated only by the volumetric quantity loss by the deformation of the shock absorber. This method is therefore considered as an effective means of evaluation provided the material can be treated under a constant compressive stress in any deformation. However, taking into account of the material properties, the VDM would have a bit problem in the view of the accuracy of solution.

The UDM, instead, will execute the evaluation under the assumption that the deformable region consists of an assembly of many one-dimensional bar elements. All volume of the shock absorber can absorb the drop energy, so that the method makes a benefit of obtaining an accurate results, although the analysis itself gets rather complicated compared with the VDM. CRUSH is computer programs which evaluate statically, for each of drop attitudes, as shown in Fig. 1.2, the cask body acceleration and shock absorber deformation in terms of the drop impact using the UDM.

In the paper, the Chapter 2 presents an illustration of calculation model and equations using UDM. The Capter 3 presents comparisons between the simplified and detailed computer programs. The Chapter 4 provides an user's input guide for CRUSH.

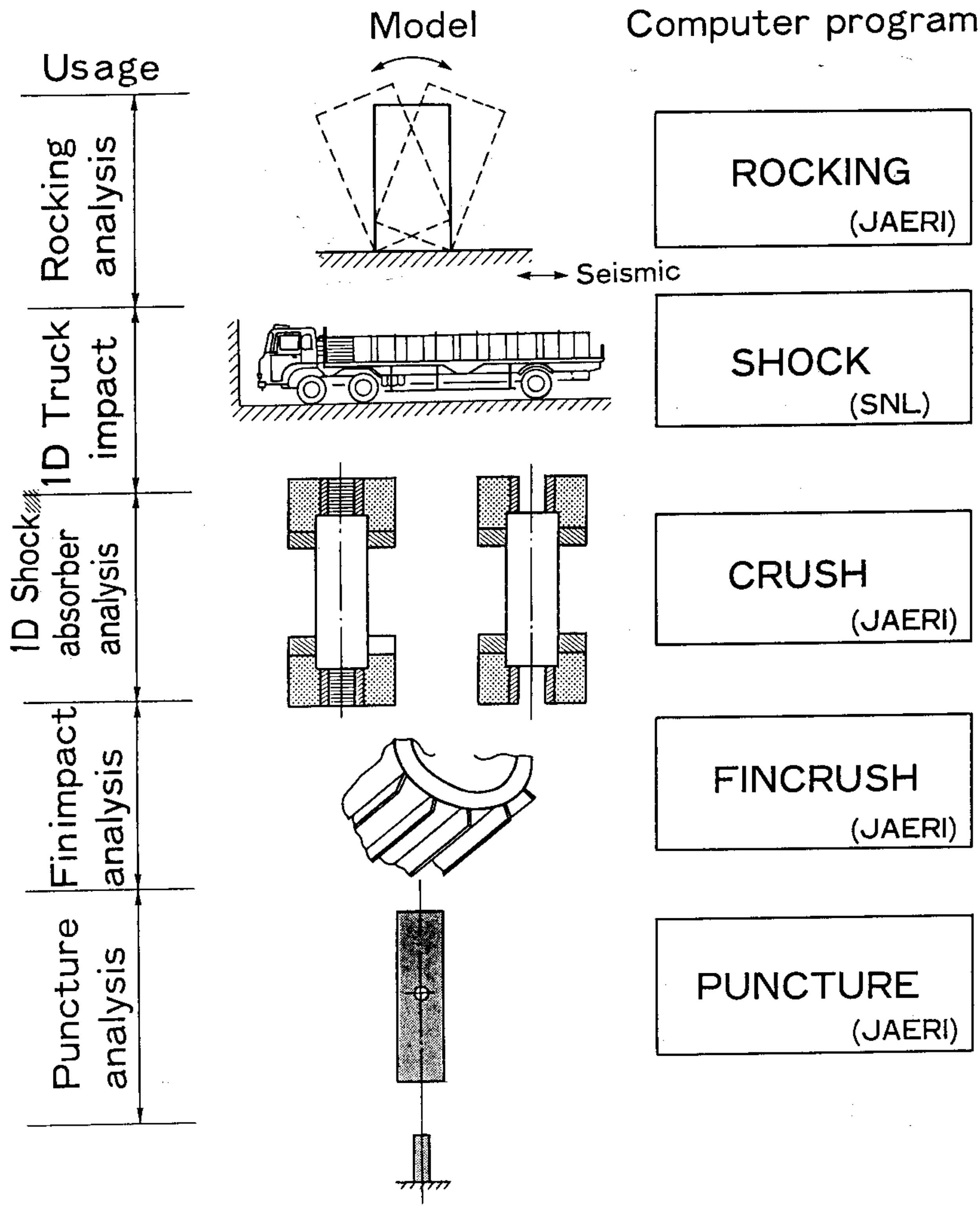
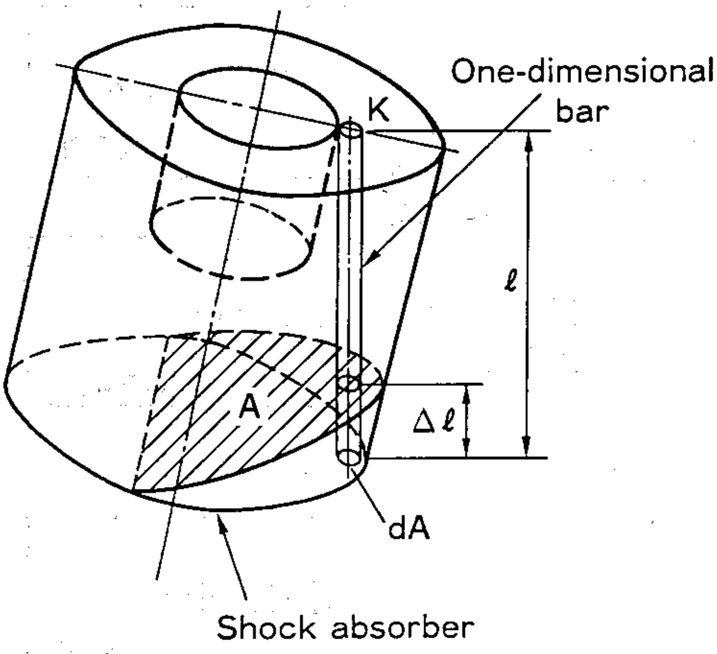


Fig. 1.1 Simplified analysis computer programs



Strain : ε

$$\varepsilon = \frac{\Delta \ell}{\ell}$$

Force :f

$$f = K\sigma(\varepsilon)dA$$

Total force : F

$$F = \int_A f\,dA$$

Acceleration : α

$$\alpha = \frac{F}{W}$$

W : Mass, A : Area

σ : Stress, K : Boundary condition constant

Fig. 1.2 Uni-axial displacement method

2. Calculation equation

2.1 Calculation model

In the modeling of shock absorber, it is assumed that the shock absorber consists of three or four species of material as shown in Figs. 2.1 to 2.3. In the figures, the symbols of $K_i (i=1\sim5)$ indicates boundary condition constants which are estimated by an overpack stiffness and boundary condition of the shock absorber.

When the shock absorber deforms by the displacement $\Delta\ell$ in a corner drop as shown in Fig. 2.4, the strain ε of an one-dimensional bar is

$$\varepsilon = \frac{\Delta\ell}{\ell} \quad . \tag{2.1}$$

The force f of the one-dimensional bar is

$$f = K\ \sigma(\varepsilon)\ \Delta A \quad . \tag{2.2}$$

where ℓ, σ an ΔA are the length, stress and area of the one-dimensional bar. K is the boundary condition constant. The total force F of the shock absorber is

$$F = \int_A f\ dA \quad . \tag{2.3}$$

The dissipated energy $E(\delta)$ can also obtained using equation similar to above Eq.(2.3)

$$E(\delta) = \int_0^{\delta} F\ d\ell \quad . \tag{2.4}$$

Therefore, when a cask whose weight of W is dropped from a height H with an oblique angle θ, the maximum displacement of the shock absorber δ and the maximum acceleration of the cask body α are given as follows.

$$E(\delta) = \gamma \cdot W \cdot H \quad , \tag{2.5}$$

$$\alpha = \frac{F(\delta)}{M} \quad , \tag{2.6}$$

where γ is the ratio of the energy absorbed in the primary impact to the total energy absorbed in the primary and secondary impacts. M is mass of the cask.

2.2 Vertical drop impact

In the modeling a shock absorber in CRUSH, it is assumed that the shock absorber consists of three or four species of shock absorber materials as shown in Fig. 2.5. In the figure, the symbols of σ_A, σ_B, σ_C, σ_D indicate their materials determined by the geometries of the cask and the shock absorber.

When the shock absorber deforms by a displacement Z in a vertical drop, the impact load F and the dissipated energy E are given by following equations.

$$F = F_{01} + F_{12} + F_{23} + F_{34} + F_{45} \quad , \tag{2.7}$$

$$E = \int_0^Z F \, dZ \quad , \tag{2.8}$$

where, for the region $0 \sim R_1$

$$F_{01} = K_1 \, \pi \, \sigma_D(\frac{Z}{Z_2}) \, R_1{}^2 \quad , \tag{2.9}$$

for the region $R_1 \sim R_2$

$$F_{12} = K_2 \, \pi \, \sigma_A(\frac{Z}{Z_2})(R_2{}^2 - R_1{}^2) \quad , \tag{2.10}$$

for the region $R_2 \sim R_3$

$$F_{23} = K_3 \, \pi \, \sigma_B(\frac{Z}{Z_2})(R_3{}^2 - R_1{}^2) \quad , \tag{2.11}$$

for the region $R_3 \sim R_4$

$$\left.\begin{aligned} F_{34} &= K_4\ \pi\ \sigma_B\left(\frac{\Delta Z_B}{Z_3}\right)(R_4^{\,2}-R_3^{\,2});\ (\text{for } \sigma_B \text{ material}), \\ F_{34} &= K_4\ \pi\ \sigma_C\left(\frac{\Delta Z_C}{Z_4-Z_3}\right)(R_4^{\,2}-R_3^{\,2});\ (\text{for } \sigma_C \text{ material}), \end{aligned}\right\} \quad (2.12)$$

$$\left.\begin{aligned} Z &= \Delta Z_B + \Delta Z_C \ , \\ \sigma_B\left(\frac{\Delta Z_B}{Z_3}\right) &= \sigma_C\left(\frac{\Delta Z_C}{Z_4-Z_3}\right) \ , \end{aligned}\right\} \quad (2.13)$$

for the region $R_4 \sim R_5$

$$\left.\begin{aligned} F_{45} &= K_5\ \pi\ \sigma_B\left(\frac{\Delta Z_B}{Z_3}\right)(R_5^{\,2}-R_4^{\,2});\ (\text{for } \sigma_B \text{ material}), \\ F_{45} &= K_5\ \pi\ \sigma_C\left(\frac{\Delta Z_C}{Z_4-Z_3}\right)(R_5^{\,2}-R_4^{\,2});\ (\text{for } \sigma_C \text{ material}), \end{aligned}\right\} \quad (2.14)$$

$$\left.\begin{aligned} Z &= \Delta Z_B + \Delta Z_C \ , \\ \sigma_B\left(\frac{Z_B}{Z_3}\right) &= \sigma_C\left(\frac{\Delta Z_C}{Z_4-Z_3}\right) \ , \end{aligned}\right\} \quad (2.15)$$

$$0 \leqq K_i \leqq 1 \ .$$

σ_i(i=A,B,C,D) are stress in the material region.

2.3 Horizontal drop impact

When the shock absorber deforms by the displacement Z in a horizontal drop as shown in Figs. 2.6 to 2.8, the impact load and the dissipated energy are given by following equations.

$$F = F_{ij} = F_{01}+F_{12}+F_{23}+F_{34}+F_{45}+F_{56}+F_{67}+F_{78}+F_{89} \ , \quad (2.16)$$

$$F_{ij} = 2\int_0^{R_5} \Delta F \ dx \ , \quad (2.17)$$

$$E = \int_0^{y} F \ dy \ , \quad (2.18)$$

where, for the region $0 \sim Z_1$ and $0 \sim R_1$

$$\left.\begin{aligned}\Delta F &= K_1\ \sigma_D(\frac{\Delta y_1}{y_1})dx\cdot Z_1;\ (\text{for } \sigma_D \text{ material})\ , \\ \Delta F &= K_1\ \sigma_A(\frac{\Delta y_2}{y_2})dx\cdot Z_1;\ (\text{for } \sigma_A \text{ material})\ , \\ \Delta F &= K_1\ \sigma_B(\frac{\Delta y_3}{y_3})dx\cdot Z_1;\ (\text{for } \sigma_B \text{ material})\ ,\end{aligned}\right\} \quad (2.19)$$

$$\left.\begin{aligned}y_1 &= 2\sqrt{R_1{}^2-x^2}\ , \\ y_2 &= 2(\sqrt{R_2{}^2-x^2} - \sqrt{R_1{}^2-x^2})\ , \\ y_3 &= 2(\sqrt{R_5{}^2-x^2} - \sqrt{R_2{}^2-x^2})\ .\end{aligned}\right\} \quad (2.20)$$

$$\left.\begin{aligned}U &= \Delta y_1 + \Delta y_2 + \Delta y_3\ , \\ \sigma_D(\frac{\Delta y_1}{y_1}) &= \sigma_A(\frac{\Delta y_2}{y_2}) = \sigma_B(\frac{\Delta y_3}{y_3})\ .\end{aligned}\right\} \quad (2.21)$$

$$\left.\begin{aligned}U &= y - h;\ \left\{\begin{aligned}&U \leqq 0, \quad \text{for } \Delta F = 0 \\ &U > 0, \quad \text{for } \Delta F \neq 0\end{aligned}\right\}, \\ h &= R_5 - \sqrt{R_5{}^2-x^2}\ .\end{aligned}\right\} \quad (2.22)$$

For the region $0\sim Z_1$ and $R_1\sim R_2$

$$\left.\begin{aligned}\Delta F &= K_1\ \sigma_A(\frac{\Delta y_1}{y_1})dx\cdot Z_1;\ (\text{for } \sigma_A \text{ material})\ , \\ \Delta F &= K_1\ \sigma_B(\frac{\Delta y_2}{y_2})dx\cdot Z_1;\ (\text{for } \sigma_B \text{ material})\ .\end{aligned}\right\} \quad (2.23)$$

$$y_1 = 2\sqrt{R_2{}^2-x^2}$$

$$y = 2(\sqrt{R_5{}^2-x^2} - \sqrt{R_2{}^2-x^2})\ .$$

$$U = \Delta y_1 + \Delta y_2\ ,$$

$$\sigma_A(\frac{\Delta y_1}{y_1}) = \sigma_B(\frac{\Delta y_2}{y_2})\ . \quad (2.25)$$

For the region $0\sim Z_1$ and $R_2\sim R_3$

$$\Delta F = K_1\ \sigma_B(\frac{U}{y})dx\cdot Z_1\ , \quad (2.26)$$

$$y = 2\sqrt{R_5{}^2-x^2}\ . \quad (2.27)$$

For the region $Z_1 \sim Z_2$ and $0 \sim R_5$ equations are similar as eqs.(2.9) through (2.25) when Z_1 changes to (Z_2-Z_1) and K_1 to K .

For the region $Z_2 \sim Z_3$ and $0 \sim R_3$

$$\Delta F = K_3 \ \sigma_B(\frac{U}{y}) dx \cdot (Z_3 - Z_2) \quad , \tag{2.28}$$

where

$$y = \sqrt{R_5{}^2 - x^2} - \sqrt{R_3{}^2 - x^2} \quad . \tag{2.29}$$

For the region $Z_2 \sim Z_3$ and $R_3 \sim R_5$

$$\Delta F = K_3 \ \sigma_B(\frac{U}{y}) dx \cdot (Z_3 - Z_2) \quad , \tag{2.30}$$

where

$$y = 2\sqrt{R_5{}^2 - x^2} \quad . \tag{2.31}$$

For the region $Z_3 \sim Z_4$ and $0 \sim R_3$

$$\Delta F = K_4 \ \sigma_C(\frac{U}{y}) dx \cdot (Z_3 - Z_2) \quad , \tag{2.32}$$

where

$$y = \sqrt{R_5{}^2 - x^2} - \sqrt{R_3{}^2 - x^2} \quad . \tag{2.33}$$

For the region $Z_3 \sim Z_4$ and $R_3 \sim R_5$

$$\Delta F = K_4 \ \sigma_C(\frac{U}{y}) dx \cdot (Z_4 - Z_3) \quad , \tag{2.34}$$

where

$$y = 2\sqrt{R_5{}^2 - x^2} \quad . \tag{2.35}$$

For the region $Z_5 \sim Z_6$ equations are same as the region $Z_3 \sim Z_4$, the region $Z_6 \sim Z_7$ same as the region $Z_2 \sim Z_3$, the region $Z_7 \sim Z_8$ same as the region $Z_1 \sim Z_2$ and the region $Z_8 \sim Z_9$ same as the region $0 \sim Z_1$.

2.4 Oblique drop impact

In the modeling a shock absorber in CRUSH at a ablique drop impact, it is assumed that the shock absorber consists of one specy of shock absorber material as shown in Fig. 2.3. The stress of a wooden shock absorber can be written as following, including the effect of the wood grain angle θ.

$$\sigma_X = \sigma_A \cos^2\theta + \sigma_B \sin^2\theta \quad , \tag{2.36}$$

where σ_A, σ_B and σ_X are stresses in the wood whose grain direction is parallel, perpendicular and angle θ degree to the drop direction, respectively.

Let consider a cutway section of a shock absorber as shown in Figs. 2.9, 2.10 and 2.11. The impact load and the dissipated energy are given by following equations (see Fig. 2.11).

$$F_i = 2\int_0^{x_M} \Delta F \, dx \quad , \tag{2.37}$$

$$F = \int_S F_i \, dS \quad , \tag{2.38}$$

$$E = \int_0^{y} F \, dy \quad , \tag{2.39}$$

$$U = y - h_0 - h; \quad \left\{ \begin{array}{ll} U \leqq 0, & \text{for } \Delta F = 0 \\ U > 0, & \text{for } \Delta F \neq 0 \end{array} \right\} \quad . \tag{2.40}$$

Sectional figures of the shock absorber in the case of oblique drop are shown in Figs. 2.12 and 2.13.

Let consider S-T coordinate as shown in Fig. 2.14.

The coordinates of points $P_1 \sim P_{12}$ and $Q_1 \sim Q_4$ are as follows.

$$\left.\begin{array}{ll}
P_1 & \{ -R_5\cos\theta \;,\; R_5\sin\theta \} \\
P_2 & \{ -R_1\cos\theta \;,\; R_1\sin\theta \} \\
P_3 & \{ R_1\cos\theta \;,\; -R_1\sin\theta \} \\
P_4 & \{ R_5\cos\theta \;,\; -R_5\sin\theta \} \\
P_5 & \{ -R_3\cos\theta + Z_2\sin\theta, \; R_3 \mathrm{cin}\theta + Z_2\cos\theta \} \\
P_6 & \{ -R_1\cos\theta + Z_2\sin\theta, \; R_1\sin\theta + Z_2\cos\theta \} \\
P_7 & \{ R_1\cos\theta + Z_2\sin\theta, \; -R_1\sin\theta + Z_2\cos\theta \} \\
P_8 & \{ R_3\cos\theta + Z_2\sin\theta, \; -R_3\sin\theta + Z_2\cos\theta \} \\
P_9 & \{ -R_5\cos\theta + Z_4\sin\theta, \; R_5\sin\theta + Z_4\cos\theta \} \\
P_{10} & \{ -R_3\cos\theta + Z_4\sin\theta, \; R_3\sin\theta + Z_4\cos\theta \}
\end{array}\right\} \tag{2.41}$$

$$\left.\begin{array}{ll} P_{11} & \{ R_3\cos\theta + Z_4\sin\theta, \quad -R_3\sin\theta + Z_4\cos\theta\} \\ P_{12} & \{ R_5\cos\theta + Z_4\sin\theta, \quad -R_5\sin\theta + Z_4\cos\theta\} \\ Q_2 & \{-R_1\cos\theta + Z_1\sin\theta, \quad R_1\sin\theta + Z_1\cos\theta\} \\ Q_3 & \{ R_1\cos\theta + Z_1\sin\theta, \quad -R_1\sin\theta + Z_1\cos\theta\} \\ Q_0 & \{ Z_2\sin\theta \quad , \quad Z_2\cos\theta \} \\ Q_4 & \{ R_4\cos\theta + Z_4\sin\theta, \quad -R_4\sin\theta + Z_4\cos\theta\} \end{array}\right]$$

The length of h_0 as shown in Figs. 2.12 and 2.13 are as follows.

When $\sigma_D \neq 0$

$$\left.\begin{array}{l} h_0 = R_5\sin\theta - \dfrac{\sin\theta}{\cos\theta} S \quad ; \text{(region } P_1\sim P_2 \text{ and } P_3\sim P_4\text{)} , \\ h_0 = \dfrac{\cos\theta}{\sin\theta} (S - R_5\cos\theta); \text{(region } P_4\sim P_{12}\text{)} . \end{array}\right\} \quad (2.42)$$

When $\sigma_D = 0$

$$\left.\begin{array}{l} h_0 = R_5\sin\theta - \dfrac{\sin\theta}{\cos\theta} S \quad ; \text{(region } P_1\sim P_2 \text{ and } P_3\sim P_4\text{)} , \\ h_0 = \dfrac{\cos\theta}{\sin\theta} (S - R_5\cos\theta); \text{(region } P_4\sim P_{12}\text{)} , \\ h_0 = \dfrac{\cos\theta}{\sin\theta} (S + R_1\cos\theta) + (R_1 + R_5)\sin\theta; \\ \qquad\qquad \text{(region(} P_2\sim Q_2\sim P_6\text{)} , \\ h_0 = \infty \; ; \text{(region } P_6\sim Q_0\sim P_7\text{)} . \end{array}\right\} \quad (2.43)$$

The lengths of h_1, ℓ_1 and ℓ_2 are as follows.

(a) If ℓ_2 is known ($S<P_5$, $S\leqq 0$, $\ell_1=0$ and $K_h=0$), h_0, h_1 and ℓ_2 are shown in Fig. 2.15(a).

$$\left.\begin{array}{l} \ell_2 = \dfrac{R_5}{\sin\theta} \qquad\qquad ; \text{(region } P_1\sim P_9\text{)} , \\ \ell_2 = \dfrac{1}{\sin\theta\cos\theta} (Z_4\sin\theta - S); \text{(region } P_9\sim P_{10}\text{)}. \end{array}\right\} \quad (2.44)$$

When $\sigma_D \neq 0$

$$h_1 = - \frac{S}{\sin\theta\cos\theta} \quad . \qquad (2.45)$$

When $\sigma_D = 0$

$$\left.\begin{aligned} h_1 &= -\frac{S}{\sin\theta\cos\theta}; \text{ (region } P_1\sim P_2) , \\ h_1 &= \frac{R_1}{\sin\theta} \quad ; \text{ (Region } P_2\sim P_6) . \end{aligned}\right\} \tag{2.46}$$

(b) If ℓ_1 and ℓ_2 are known ($S<P_5$, $S>0$, $\sigma_D \neq 0$, $h_1=0$ and $K_h=0$), h_0, ℓ_1 and ℓ_2 are shown in Fig. 2.15(b).

$$\left.\begin{aligned} \ell_2 &= \frac{R_5}{\sin\theta} \quad ; \text{ (region } P_1\sim P_9) , \\ \ell_2 &= \frac{1}{\sin\theta\cos\theta}(Z_4\sin\theta - S); \text{ (region } P_9\sim P_{10}) , \end{aligned}\right\} \tag{2.47}$$

$$\left.\begin{aligned} \ell_1 &= \frac{S}{\sin\theta\cos\theta} \quad ; \text{ } (S\leqq P_4, \text{ region } P_2\sim P_4\sim P_{12}), \\ \ell_1 &= \frac{R_5}{\sin\theta} \quad ; \text{ } (S>P_4, \text{ region } P_2\sim P_4\sim P_{12}), \end{aligned}\right\} \tag{2.48}$$

(c) If ℓ_2 is known ($S<P_5$, $S>0$ and $\sigma_D=0$), h_0, h_1 and ℓ_1 are shown in Fig. 2.15(c) and are same as Eqs. (2.42), (2.43) and (2.43).

(d) If ℓ_2 is known ($P_5\leqq S\leqq Q_0$ and $K_h=1$), h_0, h_1, ℓ_1 and ℓ_2 are shown in Fig. 2.16(d).

$$\ell_2 = \frac{1}{\sin\theta\cos\theta}(Z_1\sin\theta - S) . \tag{2.49}$$

When $\sigma_D \neq 0$

$$\left.\begin{aligned} h_1 &= -\frac{S}{\sin\theta\cos\theta} , \\ \ell_1 &= 0 , \end{aligned}\right\} ; \text{ (for } S \leqq 0) , \tag{2.50}$$

$$\left.\begin{aligned} h_1 &= 0 , \\ \ell_1 &= \frac{S}{\sin\theta\cos\theta} , \end{aligned}\right\} ; \text{ (for } 0 < S \leqq P_4) , \tag{2.51}$$

$$\left.\begin{aligned} h_1 &= 0 , \\ \ell_1 &= \frac{R_5}{\sin\theta} , \end{aligned}\right\} ; \text{ (for } S > P_4) . \tag{2.52}$$

When $\sigma_D = 0$

$$\left.\begin{aligned} h_1 &= \frac{R_1}{\sin\theta} , \\ \ell_1 &= 0 , \end{aligned}\right\} ; \text{ (for } S \leqq P_6) , \tag{2.53}$$

$$\left.\begin{aligned} h_1 &= \frac{1}{\sin\theta\cos\theta} (Z_2\sin\theta - S) , \\ \ell_1 &= 0 , \end{aligned}\right\} ; \text{ (for } S > P_6) . \tag{2.54}$$

(e) If ℓ_1 is known ($Q_0 \leqq S \leqq P_1$, $\ell_2=0$ and $K_h=1$), h_1 and ℓ_1 are shown in Fig. 2.16(e).

For region $Q_0 \sim P_8$

$$h_1 = \frac{1}{\sin\theta\cos\theta} (S - Z_2\sin\theta) , \tag{2.55}$$

$$\left.\begin{aligned} \ell_1 &= \frac{S}{\sin\theta\cos\theta} ; \text{ (for } S < P_4) , \\ \ell_1 &= \frac{R_5}{\sin\theta} \quad ; \text{ (for } S \geqq P_4) . \end{aligned}\right\} \tag{2.56}$$

For region $P_8 \sim P_1$

$$h_1 = \frac{R_3}{\sin\theta} , \tag{2.57}$$

$$\left.\begin{aligned} \ell_1 &= \frac{S}{\sin\theta\cos\theta} ; \text{ (for } S < P_4) , \\ \ell_1 &= \frac{R_5}{\sin\theta} \quad ; \text{ (for } S \geqq P_4) . \end{aligned}\right\} \tag{2.58}$$

(f) If ℓ_1 is known ($S>P_1$, $\ell_2=0$ and $K_h=1$), h_1 and ℓ_1 are shown in Fig. 2.16(f).

$$h_1 = \frac{1}{\sin\theta\cos\theta} (S - Z_4\sin\theta) , \tag{2.59}$$

$$\left.\begin{aligned} \ell_1 &= \frac{S}{\sin\theta\cos\theta} ; \text{ (for } S < P_4) , \\ \ell_1 &= \frac{R_5}{\sin\theta} \quad ; \text{ (for } S \geqq P_4) . \end{aligned}\right\} \tag{2.60}$$

The sectional fogure of the shock absorber in the case of the oblique drop impact as shown in Fig. 2.17, is an ellipoid. The equation of the ellipsoid is as follows.

$$\frac{x^2}{R_5{}^2} + \frac{y^2}{b^2} = 1 \quad , \tag{2.61}$$

where

$$b = \frac{R_5}{\sin\theta} \quad . \tag{6.62}$$

Rearranged eq. (2.61), using $y=h(x_M)$

$$x_M = \sqrt{b^2-h^2} \cdot \sin\theta \quad , \tag{2.63}$$

$$y = \frac{1}{\sin\theta} \sqrt{R_5{}^2-x^2} \quad . \tag{2.64}$$

Force ΔF at the sectional area (ΔS, Δx) is as follows.

$$\Delta F = K \cdot \sigma(\frac{U}{\ell}) \Delta S \cdot \Delta x ., \tag{2.65}$$

where K is the boundary condition constant as shown in Fig. 2.18.

$$0 \leqq K_i \leqq 1 \tag{2.66}$$

where

K_1 : for $\sigma_D=0$; region $P_3 \sim Q_3$,

for $\sigma_D \neq 0$; region $P_1 \sim X_1$,

K_2 : for $\sigma_D=0$; region $Q_3 \sim P_7$,

for $\sigma_D \neq 0$; region $X_1 \sim X_2$,

K_3 : for region $P_{11} \sim Q_4$,

K_4 : for region $Q_4 \sim P_{12}$.

2.5 Convergence method

The convergence methods for two or three materials in one dimensional bar in the case of the oblique drop impact, are as follows.

(1) Two materials

According to the stress-strain relation as shown in Fig. 2.19, the following equations are derived.

$$\left.\begin{aligned} \sigma_A &= \sigma_A{}^0 + K_A\,\varepsilon_A = \sigma_A{}^0 + \frac{K_A}{\ell_A}\,U_A \quad , \\ \sigma_B &= \sigma_B{}^0 + K_B\,\varepsilon_B = \sigma_B{}^0 + \frac{K_B}{\ell_B}\,U_B \quad , \end{aligned}\right\} \tag{2.67}$$

and

$$\left.\begin{aligned} U_A + U_B &= U \quad , \\ -\sigma_A + \sigma_B &= 0 \quad , \end{aligned}\right\} \tag{2.68}$$

from above two equations

$$\begin{bmatrix} 1 & 1 \\ -\dfrac{K_A}{\ell_A} & \dfrac{K_B}{\ell_B} \end{bmatrix} \begin{Bmatrix} U_A \\ U_B \end{Bmatrix} = \begin{Bmatrix} U \\ \sigma_A{}^0 - \sigma_B{}^0 \end{Bmatrix} \quad . \tag{2.69}$$

solve Eq. (2.69), we obtain U_A and U_B.

(2) Three materials

$$\begin{bmatrix} 1 & 1 & 1 \\ -\dfrac{K_A}{\ell_A} & \dfrac{K_B}{\ell_B} & 0 \\ -\dfrac{K_A}{\ell_A} & 0 & \dfrac{K_K}{\ell_K} \end{bmatrix} \begin{Bmatrix} U_A \\ U_B \\ U_K \end{Bmatrix} = \begin{Bmatrix} U \\ \sigma_A{}^0 - \sigma_B{}^0 \\ \sigma_A{}^0 - \sigma_K{}^0 \end{Bmatrix} \quad . \tag{2.70}$$

(3) Strain, stiffness and stress

Strain

$$\varepsilon_i = \frac{U_i}{\ell_i} \quad . \tag{2.71}$$

Stiffness (see Fig. 2.20)

$$K_i = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \quad . \tag{2.72}$$

Stress (see Fig. 2.20)

$$\sigma_i = \sigma_1 - K_i \cdot \varepsilon_i \quad . \qquad (2.73)$$

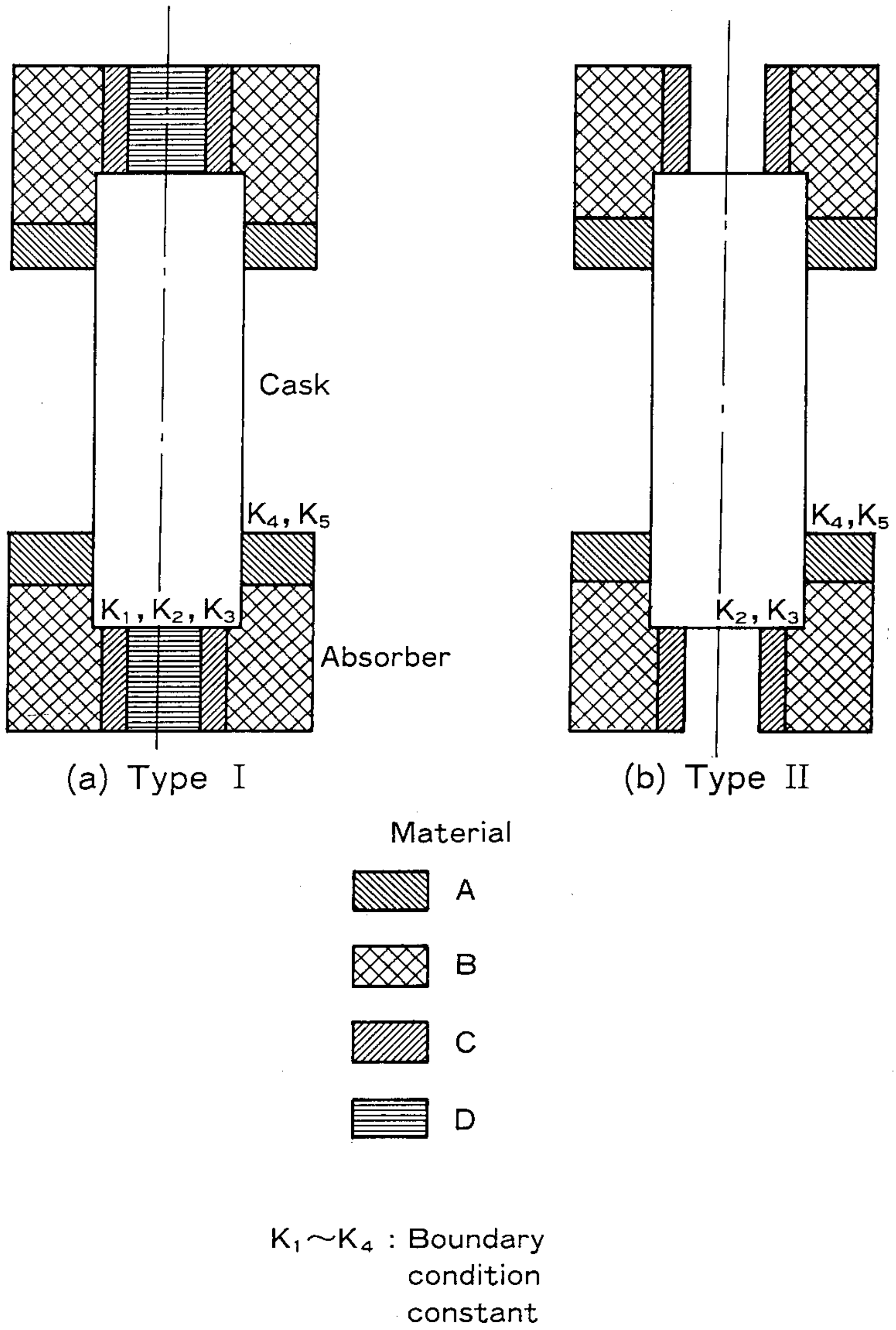


Fig. 2.1 Vertical drop model

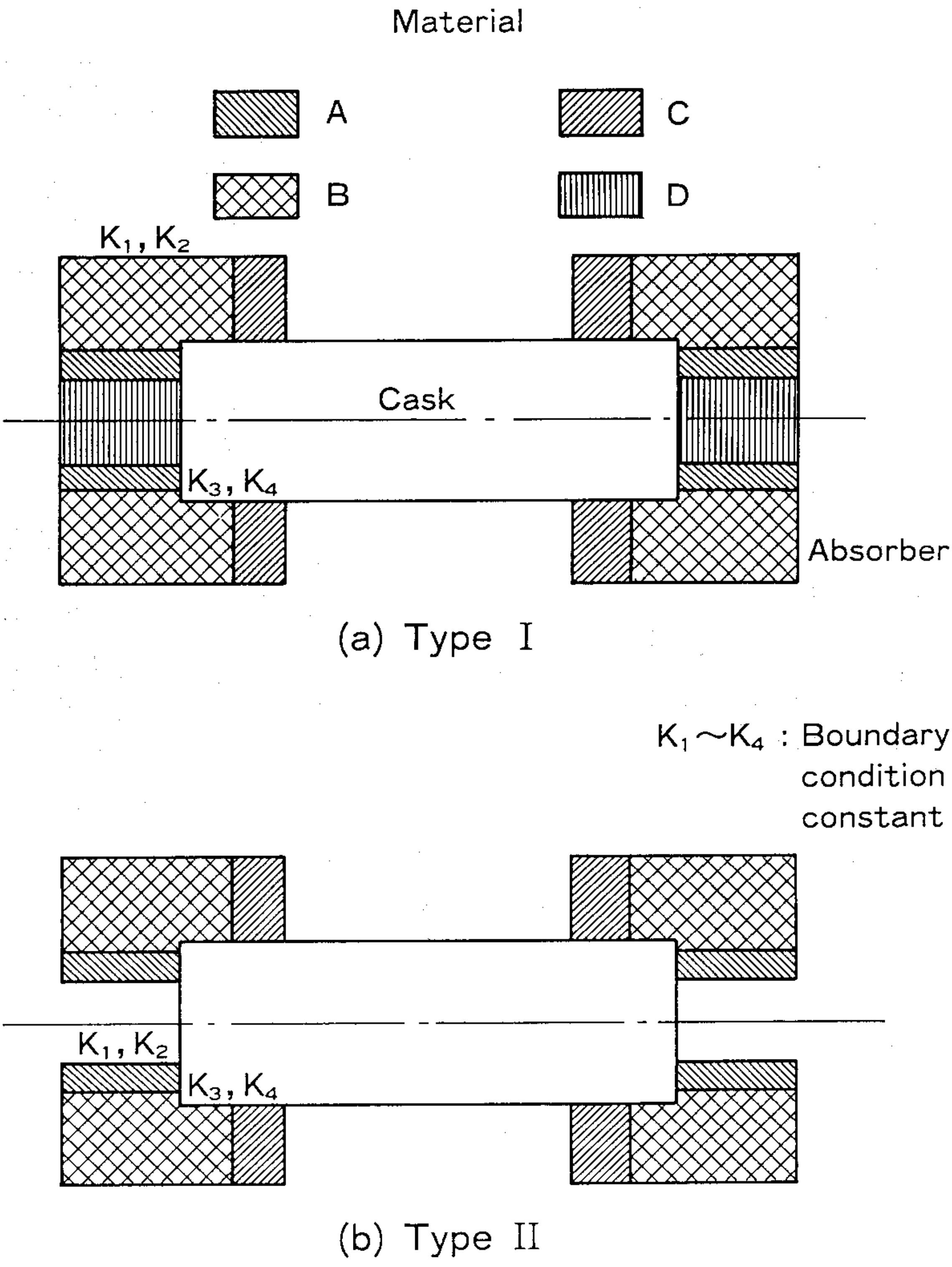


Fig. 2.2 Horizontal drop model

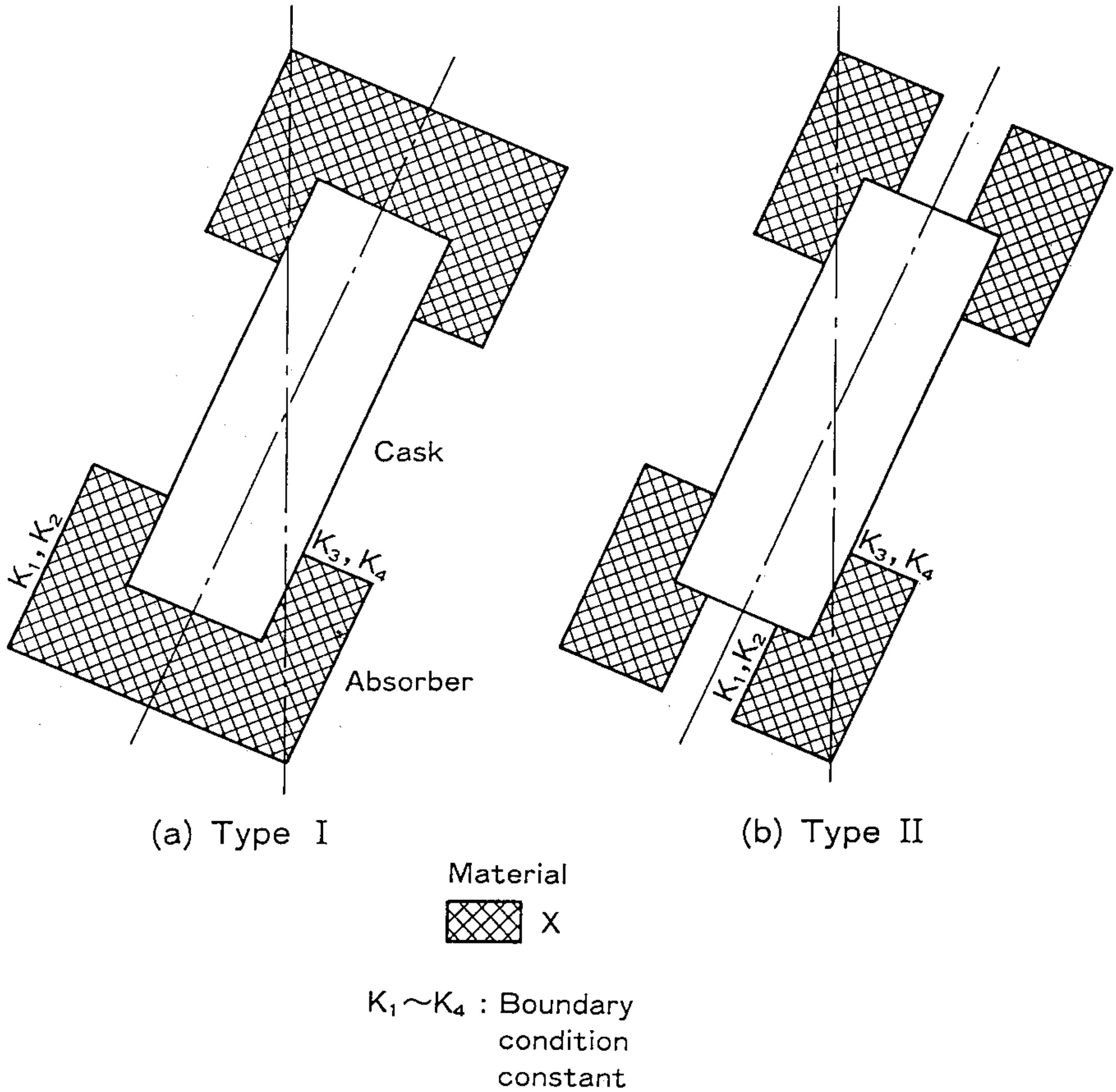
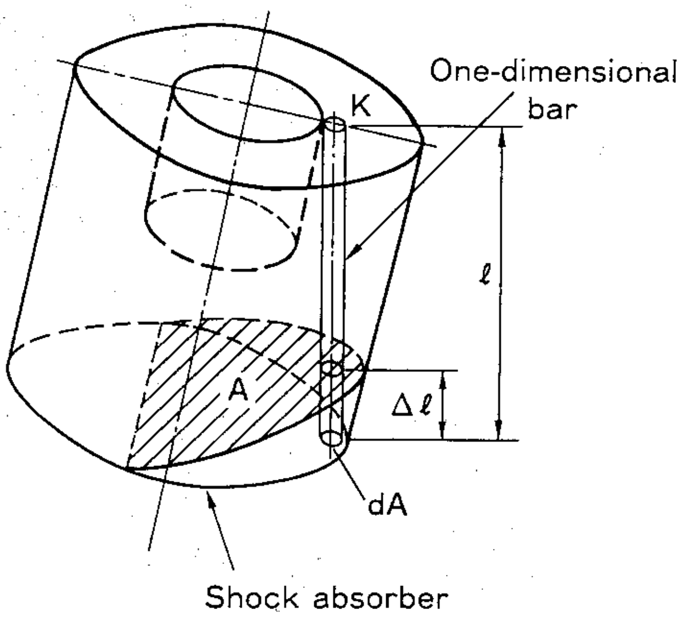


Fig. 2.3 Oblique drop model



Strain : ε

$$\varepsilon = \frac{\Delta \ell}{\ell}$$

Force : f

$$f = K\sigma(\varepsilon)dA$$

Total force : F

$$F = \int_A f\, dA$$

Acceleration : α

$$\alpha = \frac{F}{W}$$

W : Mass, A : Area

σ : Stress, K : Boundary condition constant

Fig. 2.4 Uni-axial displacement method

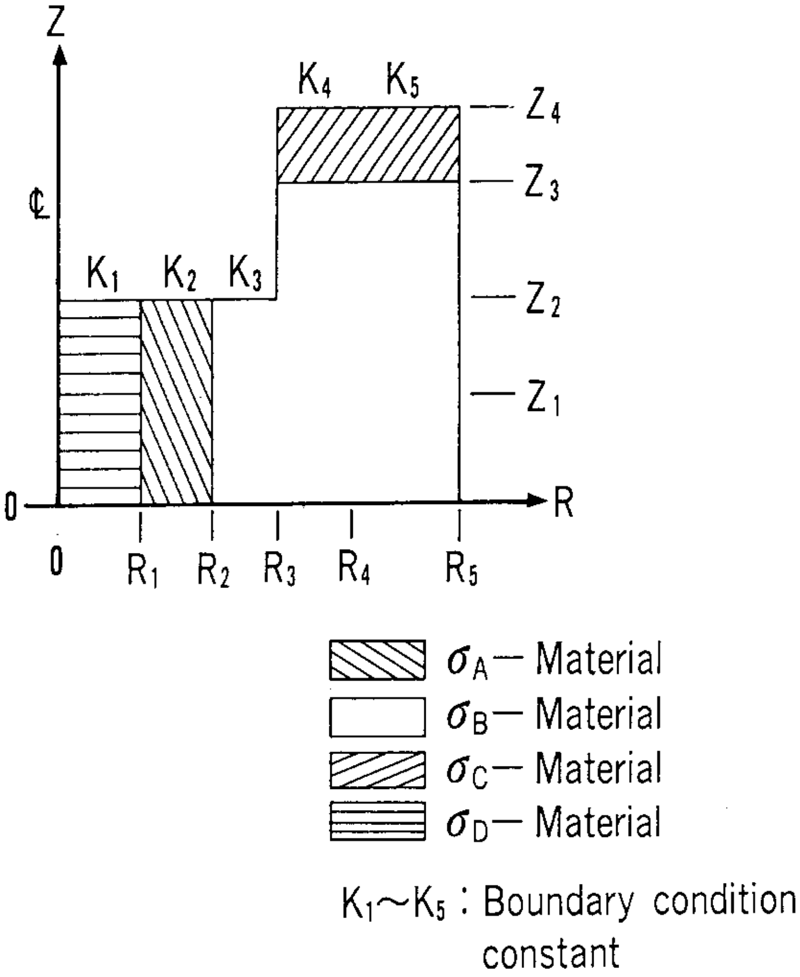


Fig. 2.5 Geometry and material in the case of vertical drop model

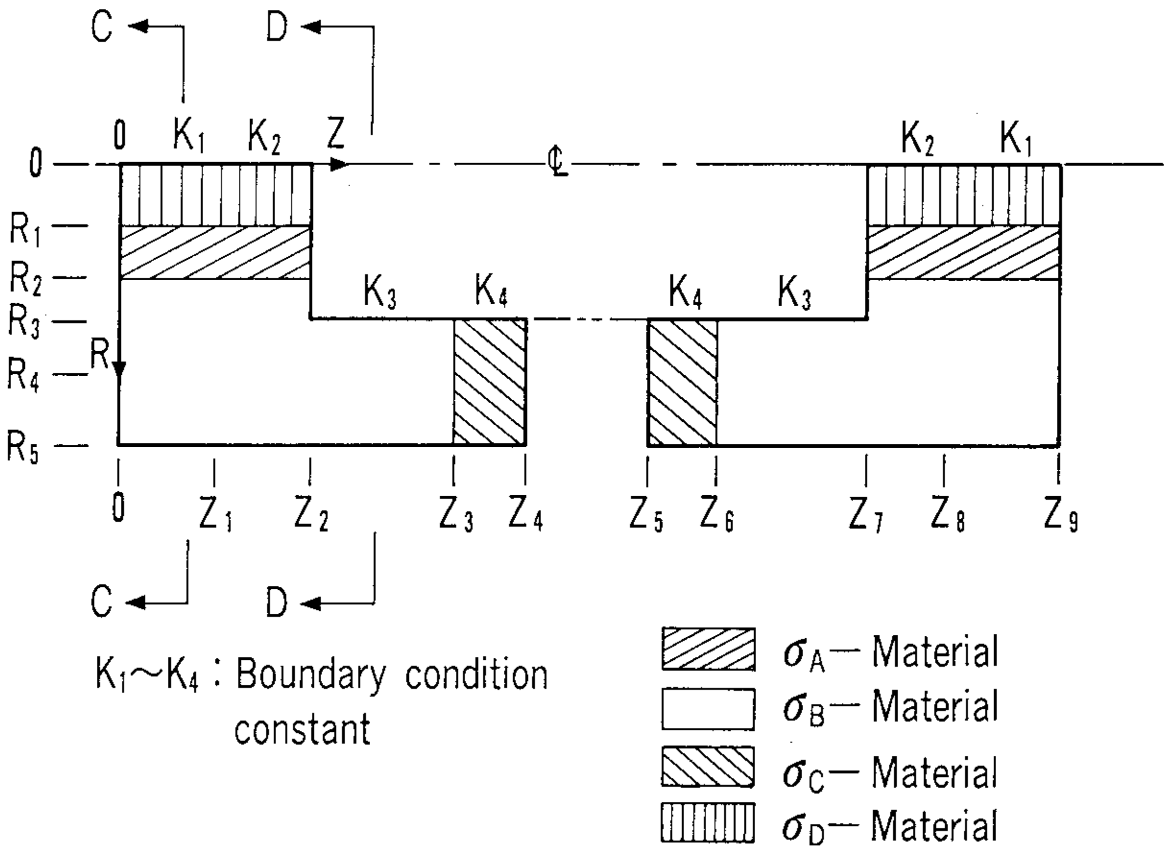


Fig. 2.6 Geometry and material in the case of horizontal drop model

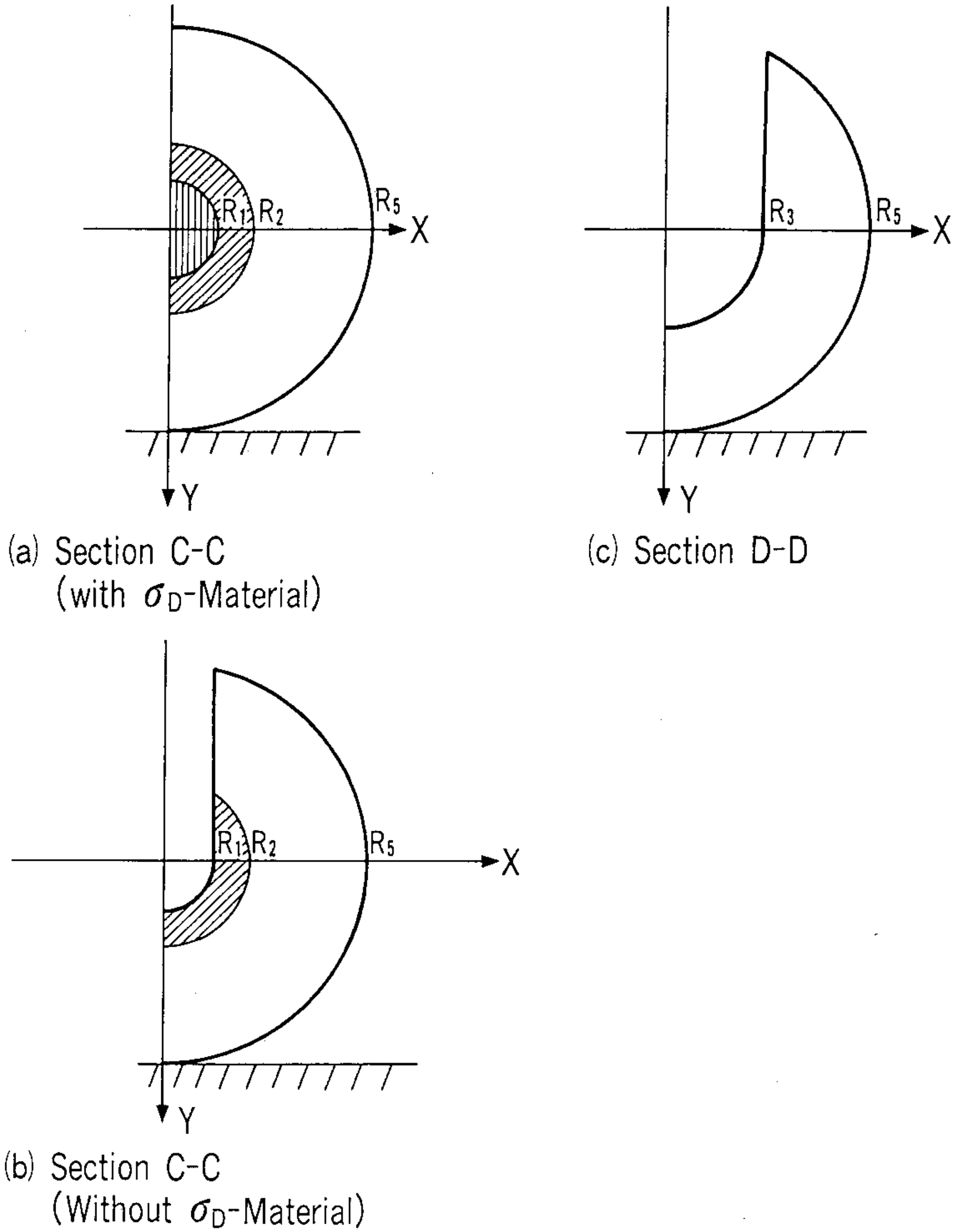


Fig. 2.7 Section view of horizontal drop model

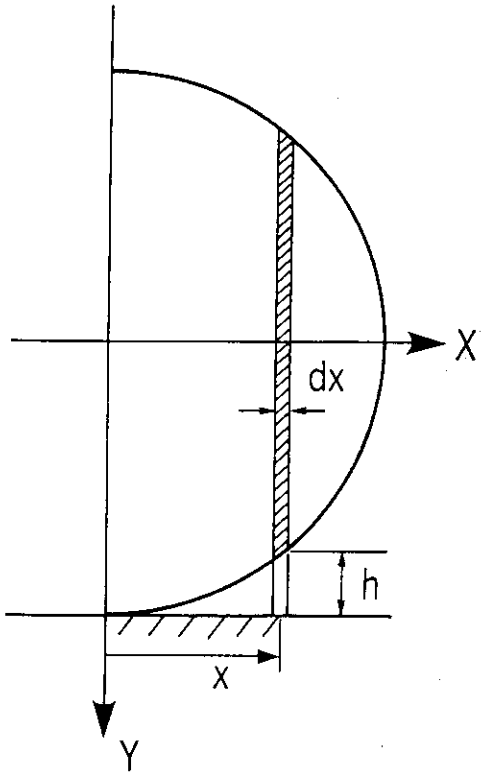


Fig. 2.8 Sectional area of shock absorber

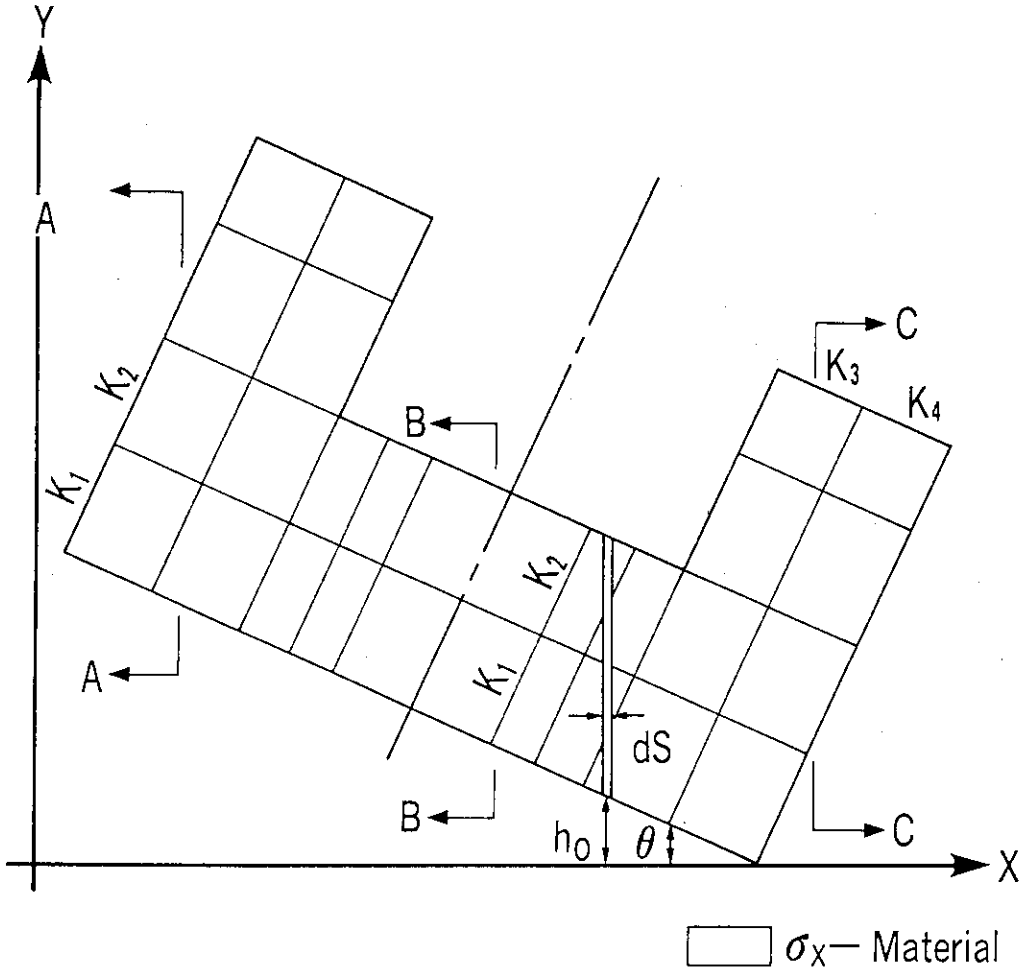


Fig. 2.9 Geometry and material in the case of oblique drop model

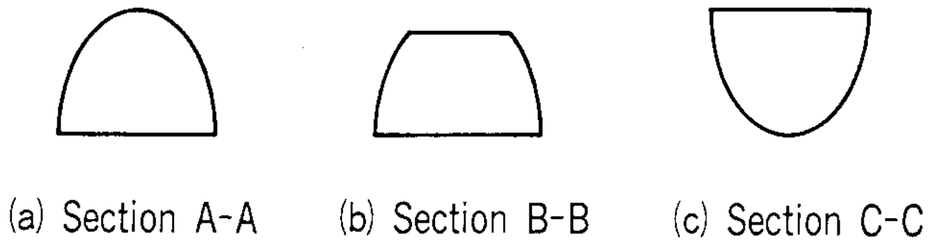


Fig. 2.10 Sectional figure of shock absorber in the case of oblique drop (I)

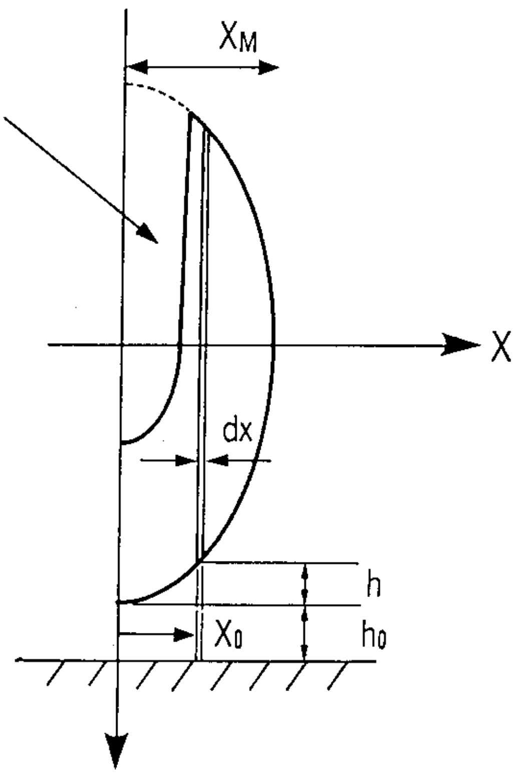


Fig. 2.11 Sectional figure of shock absorber in the case of oblique drop (II)

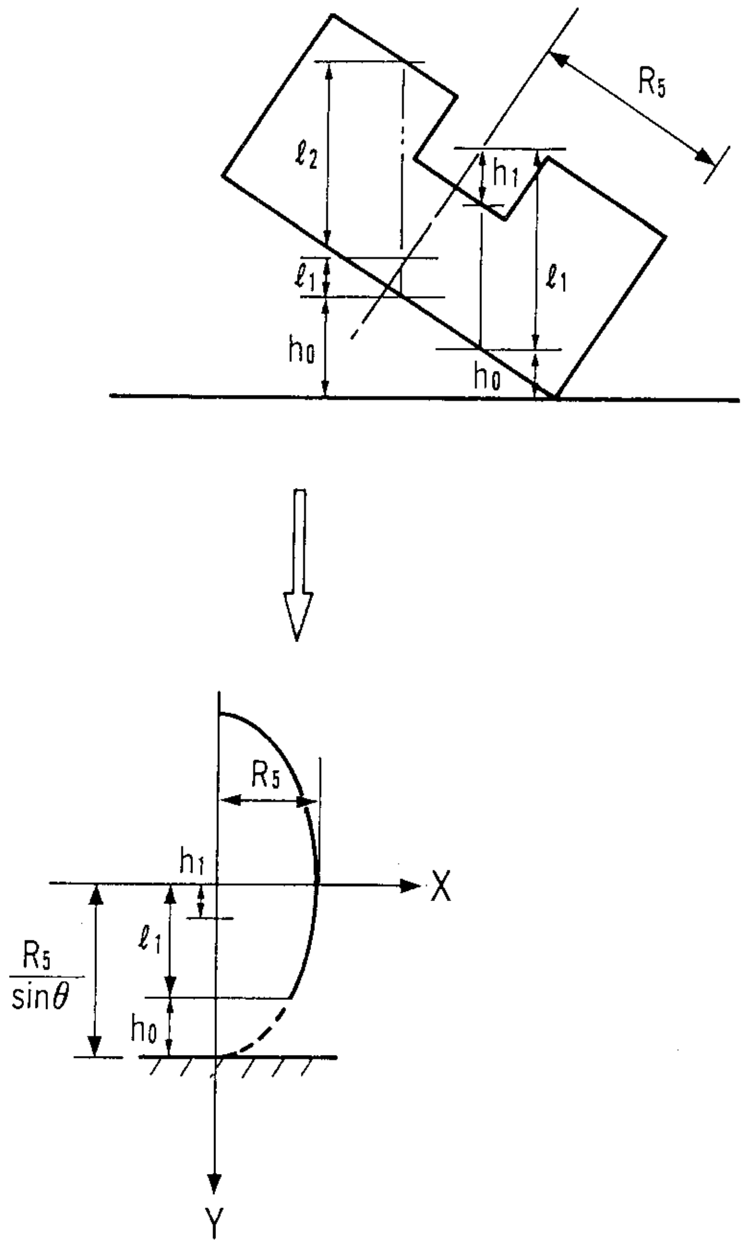


Fig. 2.12 Sectional figure of shock absorber in the case of oblique drop (III)

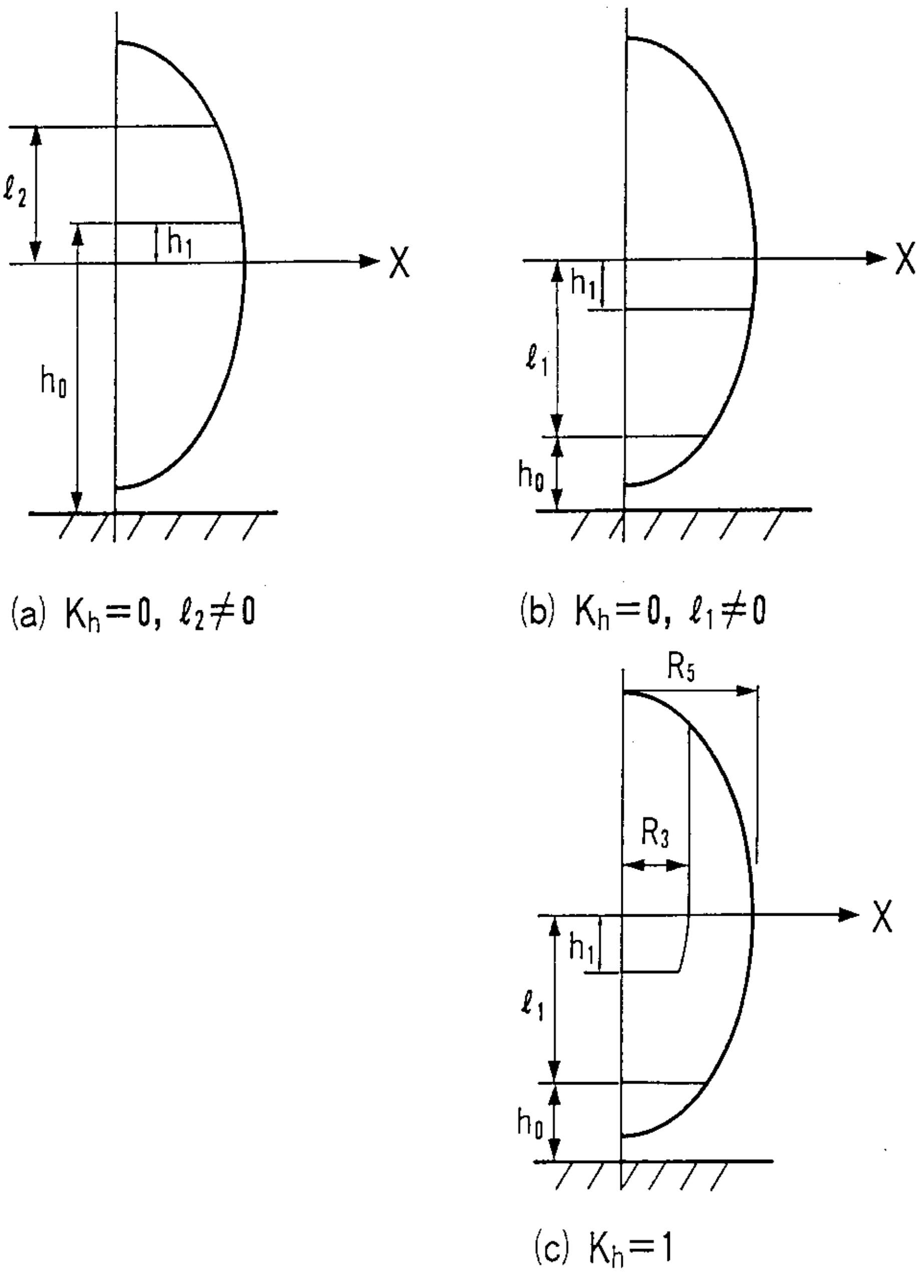


Fig. 2.13 Sectional figure of shock absorber in the case of oblique drop (IV)

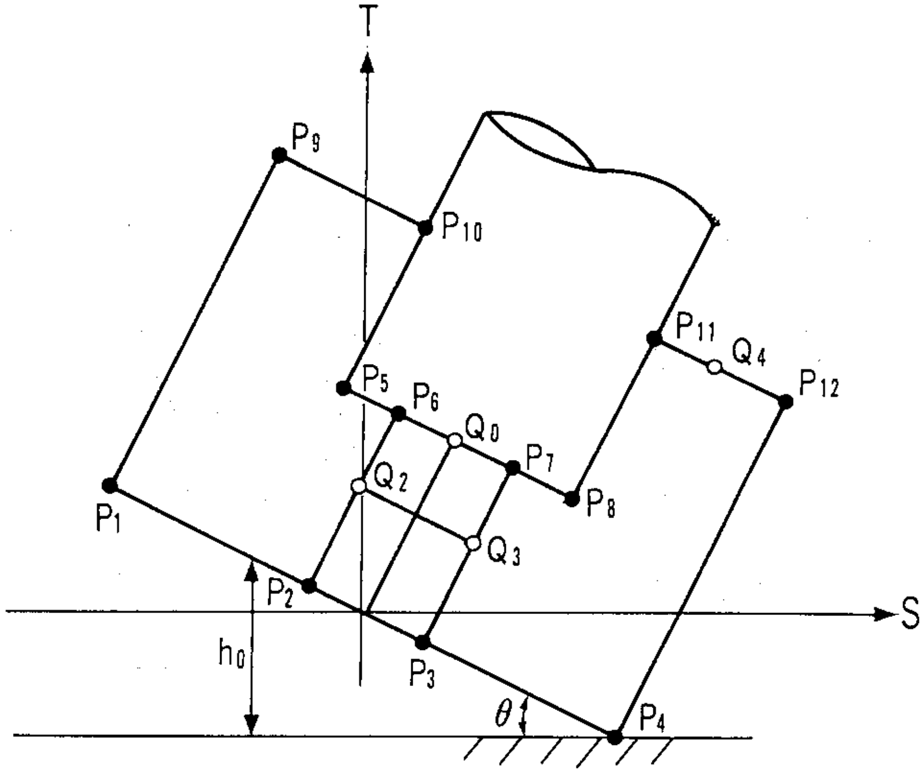


Fig. 2.14 Geometry of shock absorber in the case of oblique drop and S-T coordinate

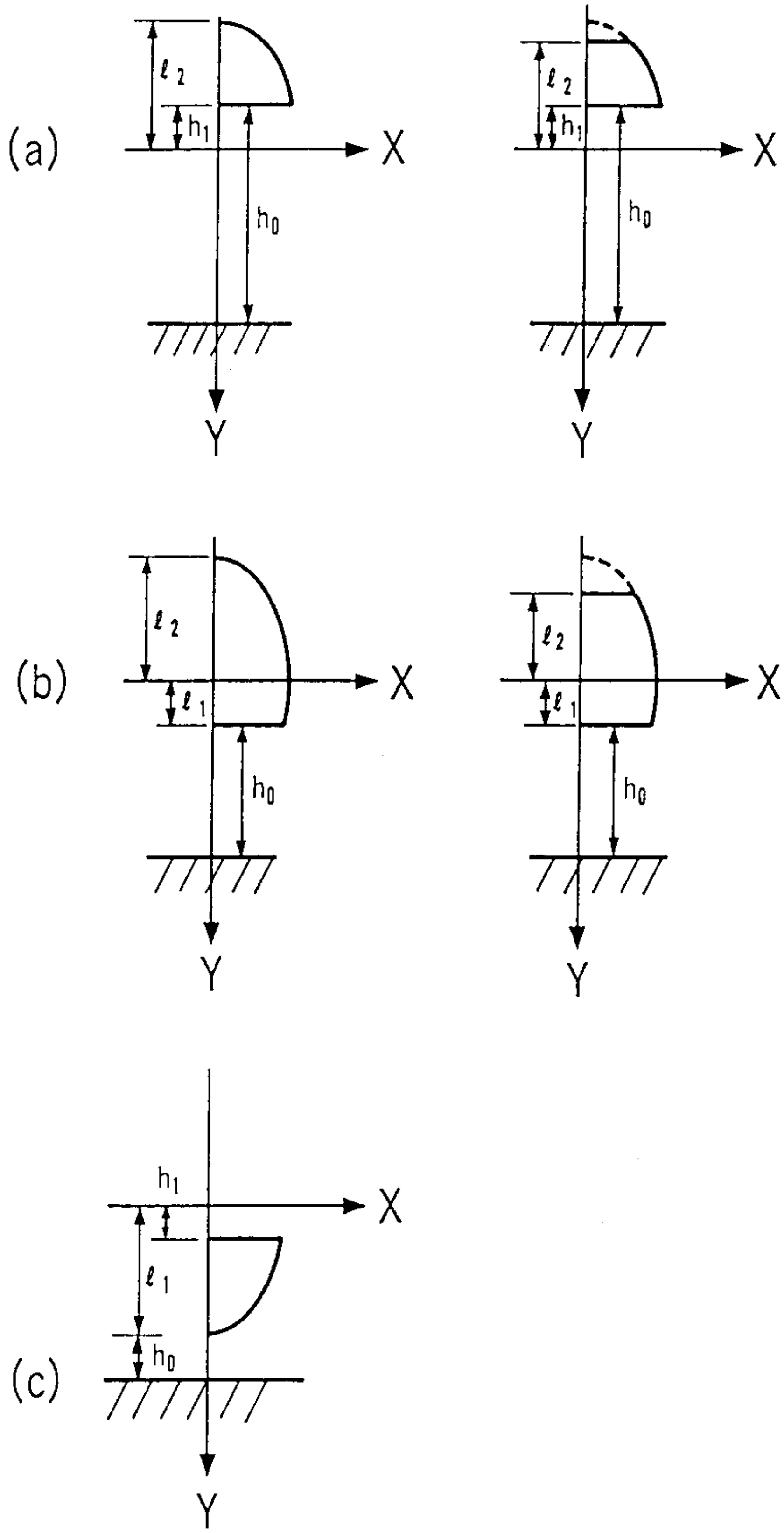


Fig. 2.15 Various sectional figure of shock absrober in the case of oblique drop (I)

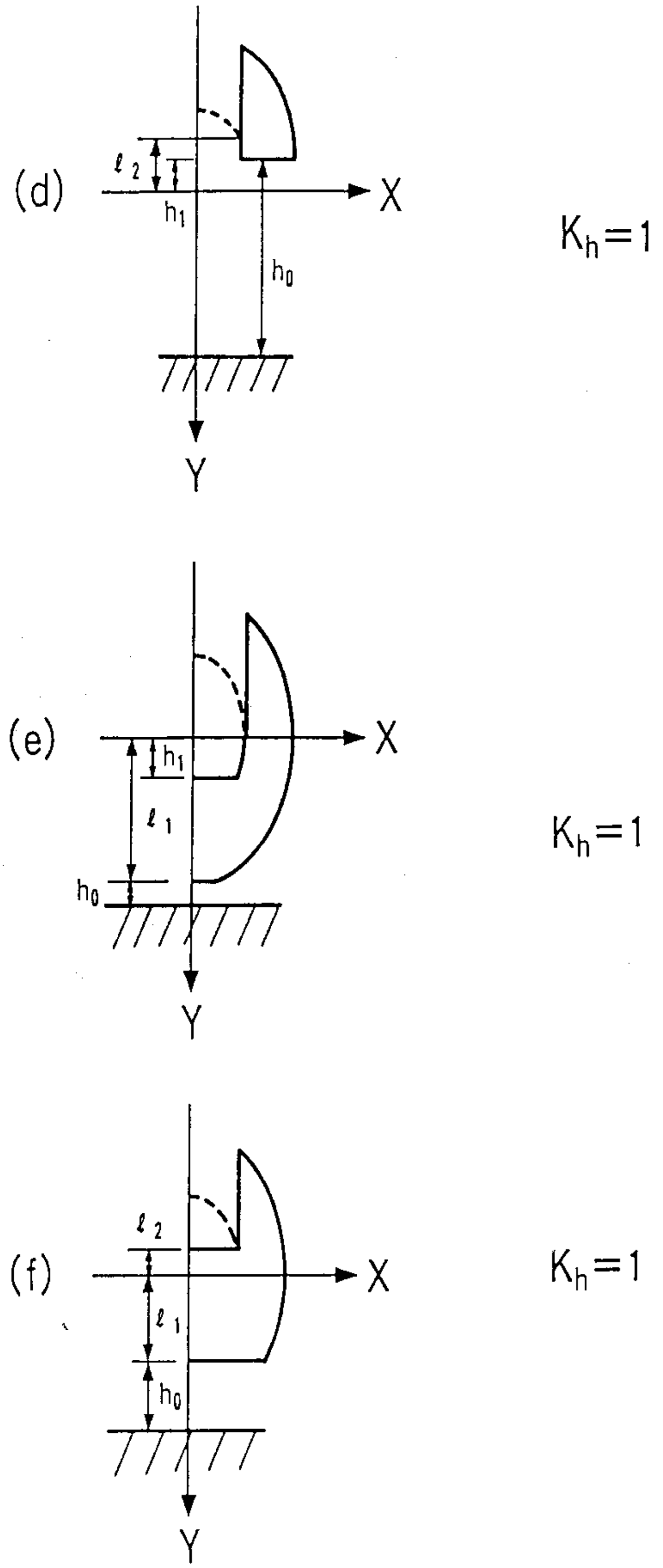


Fig. 2.16 Various sectional figure of shock absorber in the case of oblique drop (II)

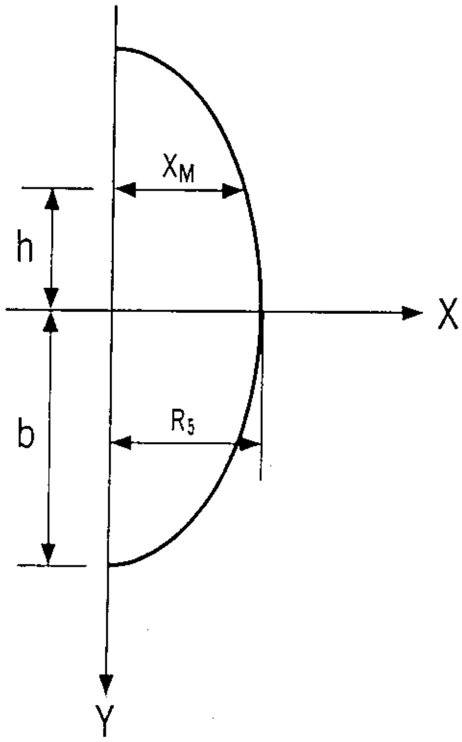


Fig. 2.17 Ellipsoid

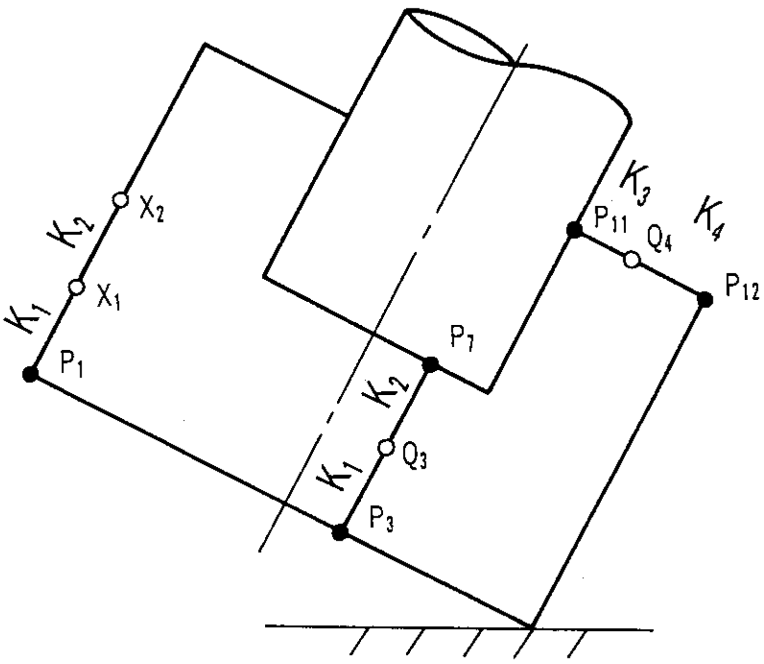


Fig. 2.18 Boundary condition constant in the case of oblique drop

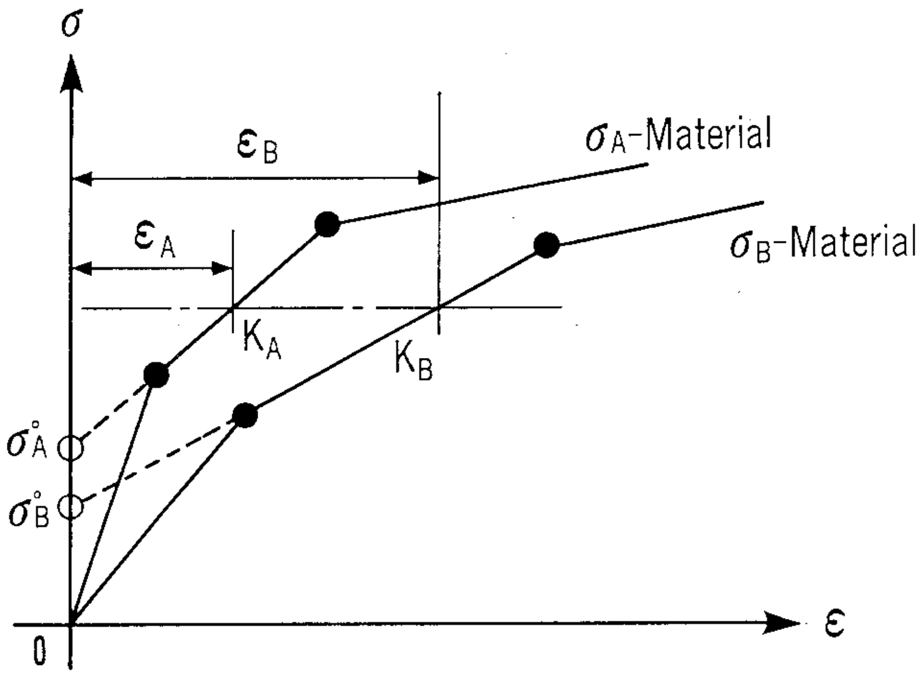


Fig. 2.19 Stress-strain curves of shock absorber materials

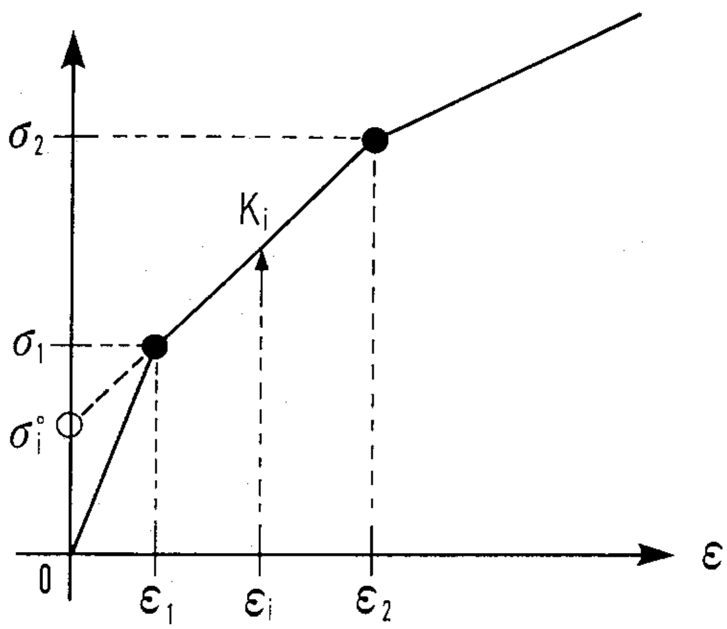


Fig. 2.20 Stress-strain curve of shock absorber material

3. Calculation Results

In order to demonstrate the adequacy of the simplified computer program CRUSH, the benchmark calculations using the experimental results of the 1/4 scale model of NUPAC 125B cask as shown in Fig. 3.1 have been performed.

Figure 3.2 is the deformed shape of the cask after 9 m drop impact to obtained by the detailed computer program DYNA3D. The comparison among the results obtained by the experiments, the simplified computer program CRUSH and the detailed computer program DYNA3D is shown in Table 3.1. The relation among the oblique angles, the acceleration and deformation obtained by CRUSH are shown in Figs. 3.3 and 3.4. According to Table 3.1 and Figs. 3.3 and 3.4, results by the simplified computer program CRUSH agree with both the experimental results and that of the results of the detailed computer program.

Table 3.1 Comparison between simplified and detailed analyses and experiment

Attitude	Acceleration (G)			Deformation (mm)		
	Experiment	Simplified analysis CRUSH	Detailed analysis DYNA3D	Experiment	Simplified analysis CRUSH	Detailed analysis DYNA3D
Vertical	200	179	271 * (200) **	51	52	50
Corner	106	125	130 (85)	127	151	132
Horizontal	180	183	216 (160)	61	63	64

* Value of low pass filter is 600 Hz.

** Mean value $= \dfrac{\text{Impact velocity}}{\text{Rebound time}}$.

(NUPAC 125 B cask ¼ scale model).

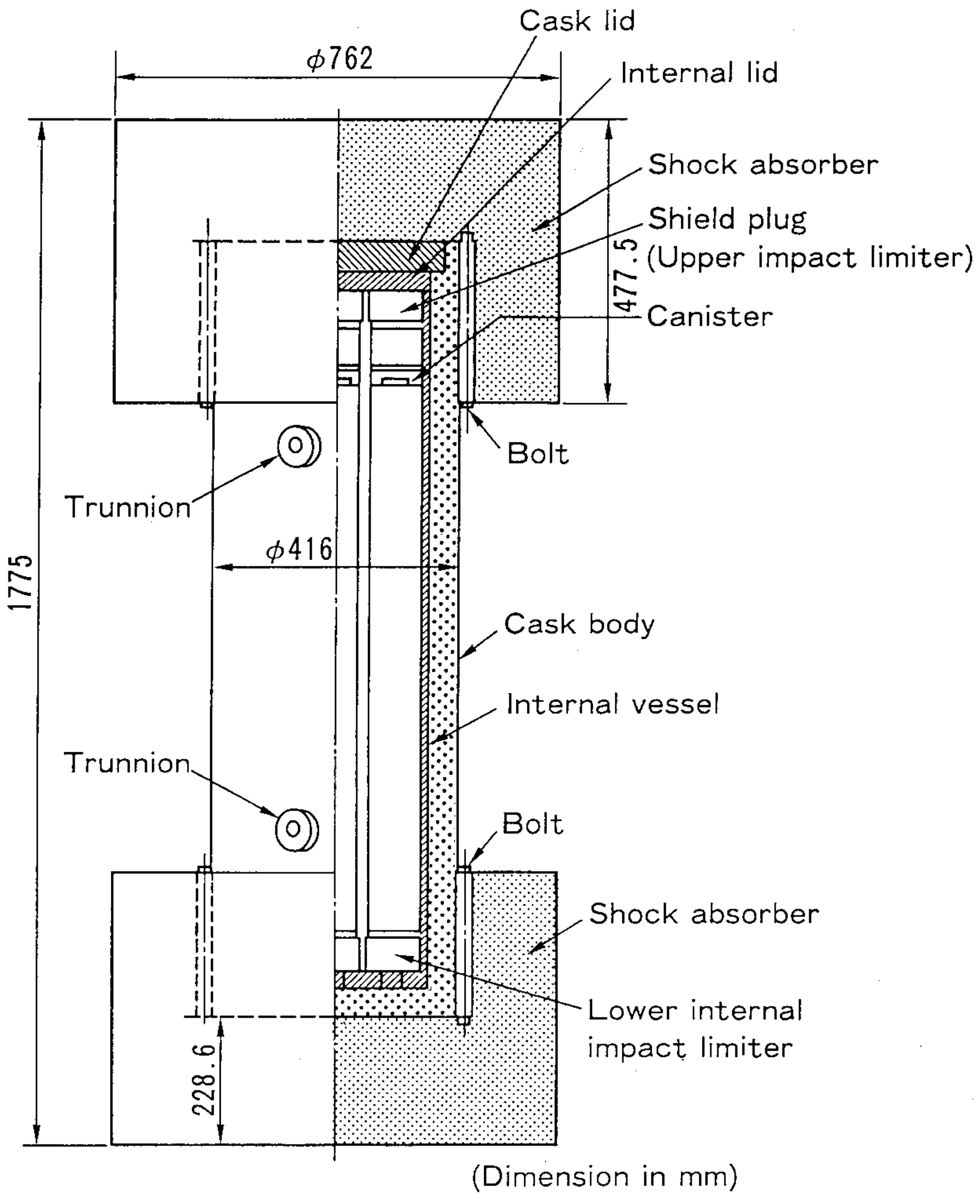


Fig. 3.1 Shipping cask-NUPAC 125B (1/4 scale model)

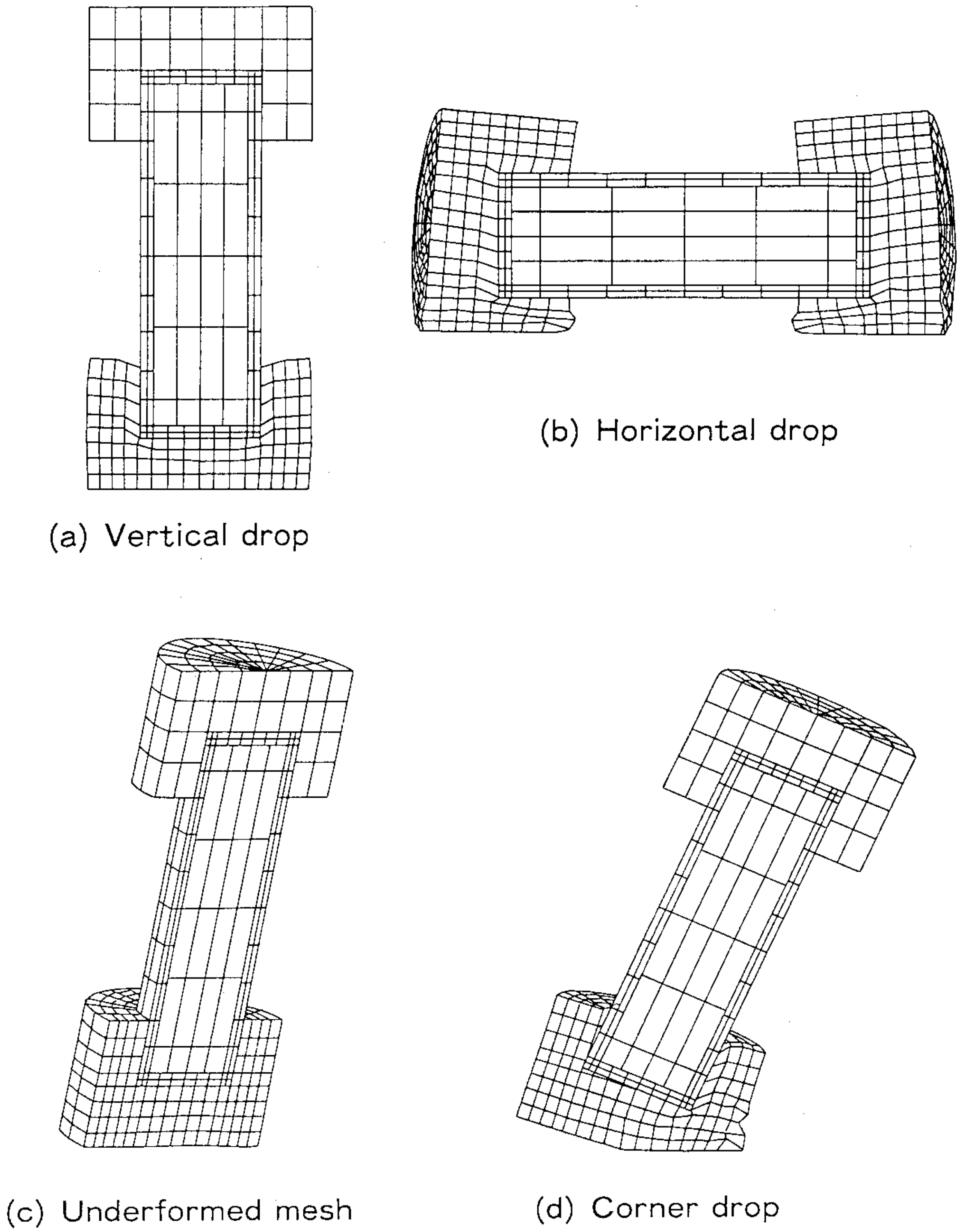


Fig. 3.2 Deformed shape after 9m drop impact
(NUPAC 125B cask 1/4 scale model)

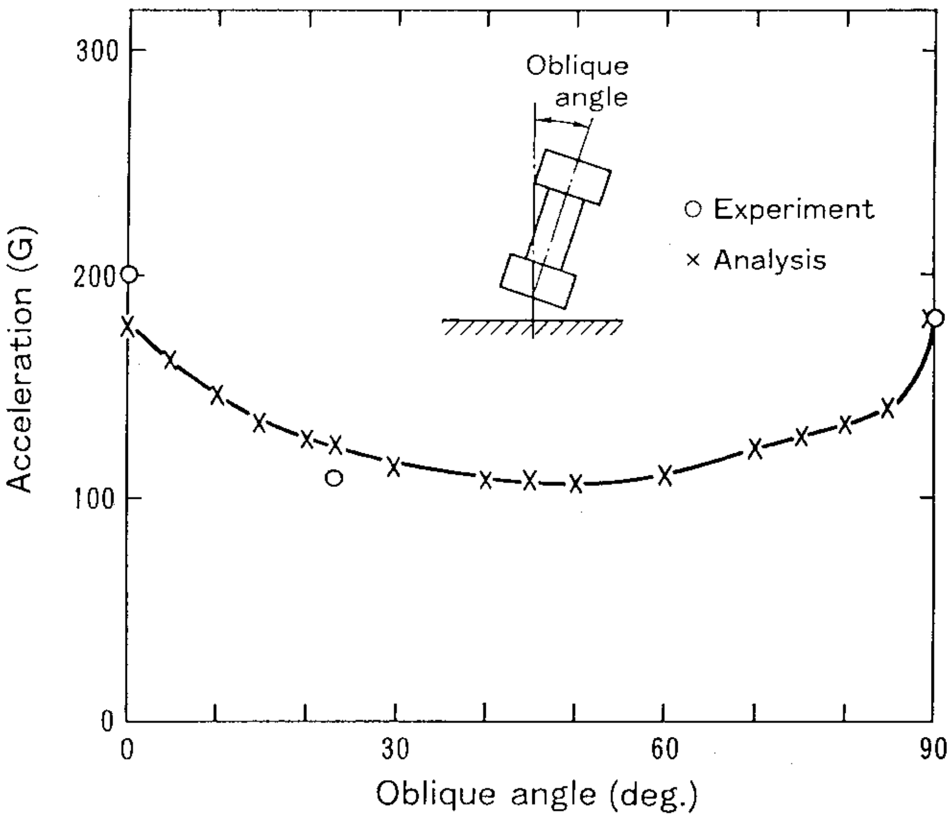


Fig. 3.3 Comparison between simplified analysis and experiment on acceleration

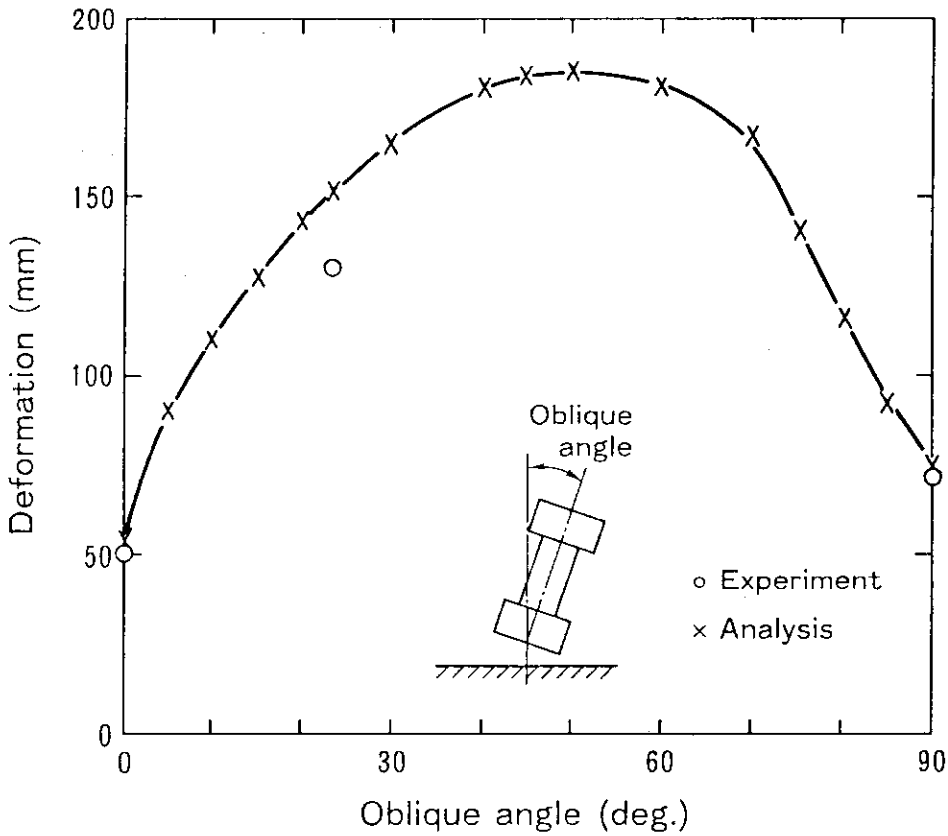


Fig. 3.4 Comparison between simplified analysis and experiment on deformation

4. Computer Program

4.1 Program Description

The computer program CRUSH is static calculation program capable of evaluating the maximum acceleration of the cask body and the maximum deformation of the shock absorber using the uniaxial displacement method.

The computer program CRUSH consists of 13 subroutines that are MAIN, CRADIN, VERT, HORIZ, CORNER, MULTI, GETMAT, EQSOLV, GETSIG, FITSTP, MPLOT, DPLOT and UPLOT. Overall structure of CRUSH is shown in Fig. 4.1. Functions of subroutines are as follows:

MAIN : initializes the start of run,

CARDIN : reads input data,

VERT : compute the acceleration and deformation in the case of vertical drop impact,

HORIZ : compute the acceleration and deformation in the case of horizontal drop impact,

CORNER : compute the acceleration and deformation in the case of oblique drop impact,

MULTI : compute the relation of stress-strain for multi-materials,

GETMAT : compute the relation of stress-strain,

EQSOLV : compute matrix,

GETSIG : compute stress,

FITSTP : fitting curve of stress-strain,

MPLOT : plotting program,

DPLOT : plotting program,

UPLOT : plotting program.

A Macroscopic flow chart of CRUSH is shown in Fig. 4.2.

4.2 Description of input data

This section describes the input data required by CRUSH. The input data consists of the job description, the analysis type such as drop attitude, geometry, the cask weight, the initial condition, the boundary condition constants, integral step, stress-strain data of the shock absorber materials, the unit selection and options for plotting. The input instruction is simple and easy to follow. The input data forms are presenten in Table 4.1.

4.3 Description of output data

This section describes the output data from CRUSH. The contents of these various output quantities are described in the followings.

(1) Input data

Input data are printed in two formats. The first print format is exactly the same as they were read. Second, the program lists the data as interpreted by the code.

(2) Calculation value

The calculation values, the deformation, the force, the energy and the acceleration are printed at every interval steps.

(3) Graphical cutput

The computer program CRUSH provides the users with graphical display output of the deformation, relationships between acceleration-deformation, dissipation energy-deformation, acceleration-dissipation energy and so on.

Table 4.1 Input data for CRUSH

Column	Format	Variable	Description
Data set No.1; Job description.			
1 - 5	5A1	JOB	TITLE.
6 - 10	5X	——	Blank.
11 - 18	70A1	TITLE	Job description.
Data set No.2; Options and geometry data.			
1 - 8	2A4	LABEL	VERTICAL: Vertical drop, HORIZONT: Horizontal drop, CORNER : Oblique drop.
9 - 10	2X	——	Blank.
11 - 20	F10.0	WEIGHT	weight of cask (kg).
21 - 30	F10.0	HEIGHT	height of cask drop (mm or cm)
31 - 40	F10.0	ANGLE	oblique angle in the case of oblique angle (deg.), (5~85 deg.).
41 - 50	F10.0	DISP	incremental deformation (mm or cm), if DISP is blank or zero, DISP equal to 1.0.
51 - 60	F10.0	CONV	truncation error, if CONV is blank or zero, CONV equal to 1.0×10^{-5}.
61 - 62	A2	IFLAG	flag for unit. IFLAG = CM unit is cm. IFLAG = MM unit is mm.
63 - 70	8X	——	blank.
71 - 80	F10.0	EMAX	maximum strain, $0.0\leq$EMAX≤1.0, if EMAX is blank or zero, EMAX equal to 1.0.
Data set No.3; Geometry data			
1 - 10	F10.0	LENGTH	length of cask body.
11 - 20	F10.0	RADIUS	radius of cask body.
21 - 25	5X	——	blank.
26 - 29	A4	DTYPE	flag for material data. DTYPE = SIGD: σ_D material exist. DTYPE = NONE: σ_D material do not exist.
Data set No.4; Options for input data check and plotting.			
1 - 5	A5	KSOLV	flag for input data check. KSOLV = RUN : execution. KSOLV = MODEL: input data check.
6 - 10	5X	——	blank.

Table 4.1 (Continued)

Column	Format	Variable	Description
11 - 14	A4	KOUT	flag for plotting KOUT = blank: no plotting. KOUT = PLOT : plotting.
15	1X	——	blank.
Data set No.5; Geometry of shock absorber (I).			
1 - 5	A5	RCOOR	RCOOR.
6 - 10	5X	——	blank.
11 - 20	F10.0	R1	radius of shock absorber (see Fig. 2.5 , 2.6 and 2.9).
21 - 30	F10.0	R2	same as above.
31 - 40	F10.0	R3	same as above.
41 - 50	F10.0	R4	same as above.
51 - 60	F10.0	R5	same as above.
Data set No.6A; Geometry of shock absorber (IIA).			
1 - 5	A5	ZCOOR	ZCOOR.
6 - 10	5X	——	blank.
11 - 20	F10.0	Z1	axial length of shock absorber (see Fig. 2.5 and 2.6).
21 - 30	F10.0	Z2	same as above.
31 - 40	F10.0	Z3	same as above.
41 - 50	F10.0	Z4	same as above.
51 - 60	F10.0	Z5	same as above.
61 - 70	F10.0	Z6	same as above.
71 - 80	F10.0	Z7	same as above.
Data set No.6B; Geometry of shock absorber (IIB).			
1 - 10	10X	——	blank.
11 - 20	F10.0	Z8	axial length of shock absorber (see Fig. 2.5 and 2.6).
21 - 30	F10.0	Z9	same as above. Data Z5 to Z9 is only used in the case of horizontal drop. If symetric case, Z5 to Z9 are omitted.
Data set No.7; Boundary condition constant.			
1 - 4	A4	MESH	MESH.
5 - 10	6X	——	blank.

Table 4.1 (Continued)

Column	Format	Variable	Description
11 - 15	I5	NPART	number of partitions in the X-Y section of horizontal or corner drop case. maximum NPART = 300. If NPART is blank or zero, NPART equal to 100.
16 - 20	I5	KPART	number of partitions in the R-Z section of corner drop case. maximum KPART = 400. If KPART is blank or zero, KPART equal to 100.
21 - 30	F10.0	K1	boundary condition constant (see Fig. 2.5, 2.6 and 2.9)
31 - 40	F10.0	K2	same as above.
41 - 50	F10.0	K3	same as above.
51 - 60	F10.0	K4	same as above.
61 - 70	F10.0	K5	same as above.
Data set No.8A;.Material data for shock absorber.			
1 - 4	A4	TYPE	flag for material data identification. SIGA: σ_A stress-strain data (see Fig. 2.5, 2.6 and 2.9). SIGB: σ_B stress-strain data. SIGC: σ_C stress-strain data. SIGD: σ_D stress-strain data. SIGX: σ_X stress-strain data.
5 - 10	5X	——	blank.
11 - 15	I5	N	number of stress-strain data.
16 - 20	5X	——	blank.
21 - 30	F10.0	FACT	factor of stress data.
Data set No.8B; Stress-strain data.			
1 - 10	F10.0	STRAIN(1)	strain (see Fig. 2.19 and 2.20).
11 - 20	F10.0	STRESS(1)	stress.
21 - 30	F10.0	STRAIN(2)	strain.
31 - 40	F10.0	STRESS(2)	stress.
------	------	---------	----------
------	------	---------	----------
61 - 70	F10.0	STRAIN(4)	strain.
71 - 80	F10.0	STRESS(4)	stress. Repeat 8B data set for N data.

Repeat 8A,8B data set for SIGA, SIGB, SIGD or SIGX stress-strain data.

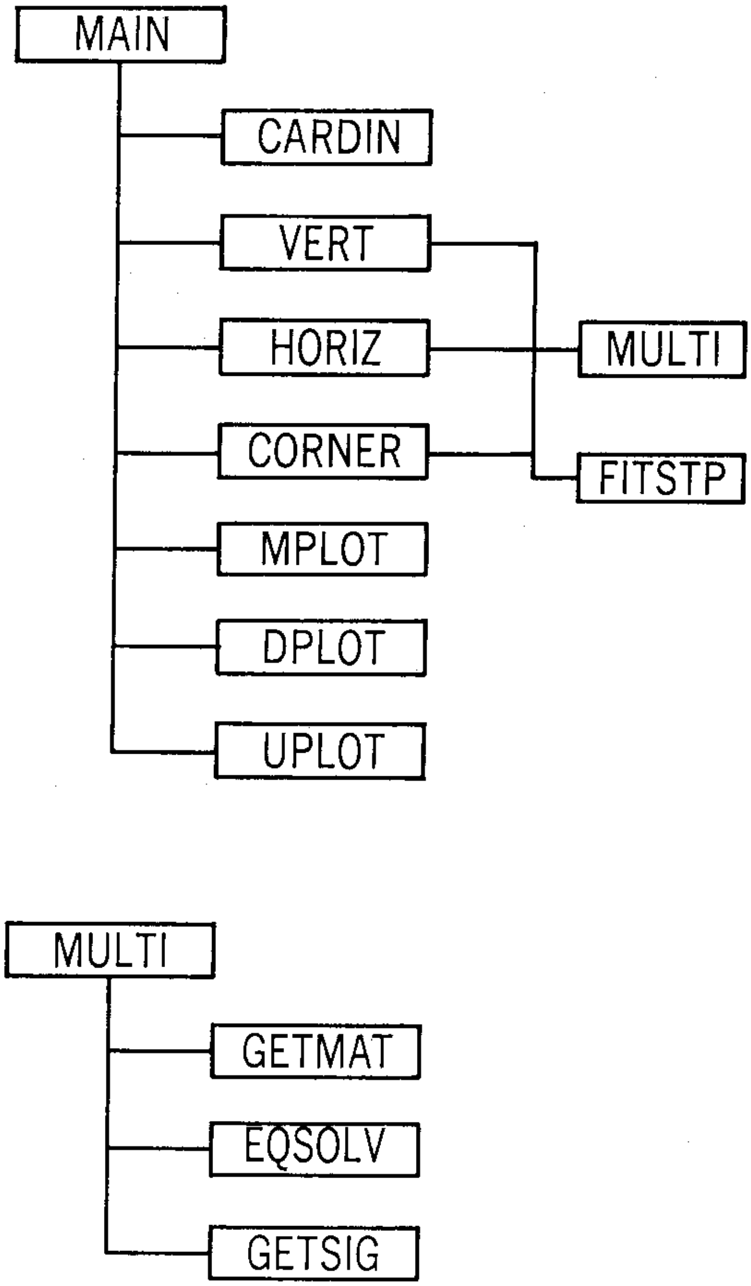


Fig. 4.1 Structure of computer program CRUSH

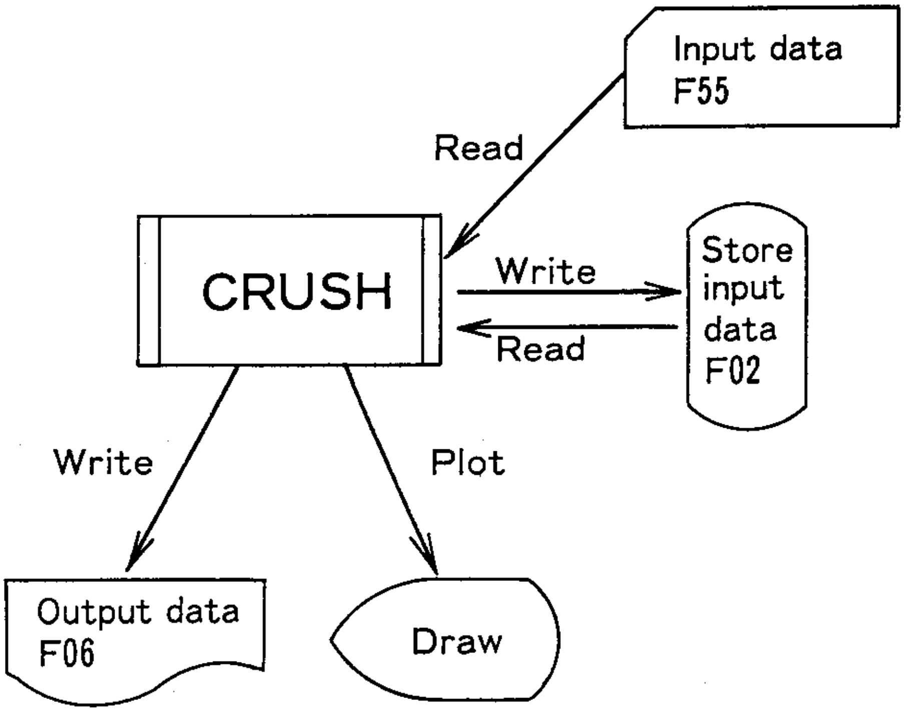


Fig. 4.2 Program flow

5. Conclusions

In regard to the evaluation of the maximum acceleration of the cask bodys and the maximum deformation of the shock absorber on the drop impact, a simplified computer program CRUSH make to analyze economical and by shortening input and computer time to about 1/50 or less as compared with other detailed computer programs to analyze dynamic interactions. The results obtained by the simplified computer program CRUSH has an enough adequacy for its practical use. CRUSH is further being utilized satisfactory in safety analysis and designing not only spent fuel transport casks but also those for various radioactive transport casks.

Acknowledgements

The author is indebted Mr. M. Ohashi, K. Asada and S. Hode of Mitsubishi Heavy Industries Ltd. for providing the sample problems and valuable discussions. He is also indebted Mr. Takashi Ishiwata of Century Research Center Ltd. for assistance of making the computer program.

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References

(1) Donham, B.J., Mathematical Model for Prediction of Maximum Damage to Shielded Shipping Containers, Tests on Transport Packaging for Radioactive Materials, Proceeding of Seminar (Vienna), IAEA pp.509-523 (1971).

(2) Tomita, N. et al., Confirmation Tests of PWR Surveillance Capsule Shipping Container, Technical Report of Mitsubishi Heavy Industries Ltd., Vol. 17, No. 3, pp.37-47 (1980).

(3) Asada, K. et al., Development of Simplified Analysis Codes for 9 m Drop and 1 m Puncture Tests for a Radioactive Material Transport Cask, Waste Management '88 (Tuscon) (1988).

Appendix A Sample problem input

```
DATA              1         2         3         4         5         6         7         8
SEQ. NO.  ----5----0----5----0----5----0----5----0----5----0----5----0----5----0----5----0

   1      TITLE     CRUSH SAMPLE PROBLEM (VERTICAL 9M DROP)                                    1
   2      VERTICAL  20000.0   9000.0    0.0       5.0       0.0       MM                       2
   3      RUN       PLOT                                                                       3
   4      RCOOR     450.0     520.0     650.0     740.0     950.0                              4
   5      ZCOOR     120.0     220.0     300.0     470.0                                        5
   6                                                                                           6
   7      MESH                1.0       1.0       1.0       0.75      0.75                     7
   8      SIGA          6     1.0                                                              8
   9      0.000     0.0       0.053     3.1       0.235     3.1       0.355     3.2            9
  10      0.520     4.25      0.600     7.0                                                   10
  11      SIGB          8     1.0                                                             11
  12      0.000     0.0       0.020     0.9       0.032     1.2       0.235     1.2           12
  13      0.300     1.25      0.420     3.0       0.500     5.55      0.545     8.0           13
  14      SIGC          8     1.0                                                             14
  15      0.000     0.0       0.020     0.9       0.032     1.2       0.235     1.2           15
  16      0.300     1.25      0.420     3.0       0.500     5.55      0.545     8.0           16

          ----5----0----5----0----5----0----5----0----5----0----5----0----5----0----5----0
                   1         2         3         4         5         6         7         8
```

Appendix B Sample problem output

```
                          C R U S H   M O D E L   D A T A

                   1         2         3         4         5         6         7         8
          ....:....0....:....0....:....0....:....0....:....0....:....0....:....0....:....0
   1-     TITLE     CRUSH SAMPLE PROBLEM (VERTICAL 9M DROP)
   2-     VERTICAL  20000.0   9000.0    0.0       5.0       0.0       MM
   3-     RUN       PLOT
   4-     RCOOR     450.0     520.0     650.0     740.0     950.0
   5-     ZCOOR     120.0     220.0     300.0     470.0
   6-
   7-     MESH                1.0       1.0       1.0       0.75      0.75
   8-     SIGA          6     1.0
   9-     0.000     0.0       0.053     3.1       0.235     3.1       0.355     3.2
  10-     0.520     4.25      0.600     7.0
  11-     SIGB          8     1.0
  12-     0.000     0.0       0.020     0.9       0.032     1.2       0.235     1.2
  13-     0.300     1.25      0.420     3.0       0.500     5.55      0.545     8.0
  14-     SIGC          8     1.0
  15-     0.000     0.0       0.020     0.9       0.032     1.2       0.235     1.2
  16-     0.300     1.25      0.420     3.0       0.500     5.55      0.545     8.0


   ...... MODEL WEIGHT  =  20000.00  (KG)
   ...... MODEL HEIGHT  =   9000.00  (MM)
   ...... CORNER ANGLE  =      0.0   (DEG.)
   ...... INCREMENT DISP=      5.00  (MM)

   ...... K-FACTOR      =      1.0000    1.0000    1.0000    0.7500    0.7500
```

Appendix B (Continued)

CRUSH SAMPLE PROBLEM (VERTICAL 9M DROP)

MODEL TYPE = VERTICAL   TOTAL ENERGY =   179999.99 (KG-M)

STEP	DEPTH (MM)	FORCE (KG)	ENERGY (KG-M)	ACCELERATION (G)
1	5.00	1287621.02	6438.10	64.38
2	10.00	2194504.85	17410.63	109.73
3	15.00	2589439.30	30357.82	129.47
4	20.00	2591845.63	43317.05	129.59
5	25.00	2591845.63	56276.28	129.59
6	30.00	2591845.63	69235.51	129.59
7	35.00	2591845.63	82194.73	129.59
8	40.00	2591845.64	95153.96	129.59
9	45.00	2591845.64	108113.19	129.59
10	50.00	2591845.64	121072.41	129.59
11	55.00	2600025.56	134072.54	130.00
12	60.00	2612419.38	147134.64	130.62
13	65.00	2624813.20	160258.70	131.24
14	70.00	2757223.02	174044.82	137.86
15	70.50	2773464.40	175431.55	138.67
16	71.00	2789705.79	176826.40	139.49
17	71.50	2805947.17	178229.38	140.30
18	72.00	2822188.56	179640.47	141.11
19	72.13	2826302.84	179999.99	141.32

Appendix C Graphical output of CRUSH

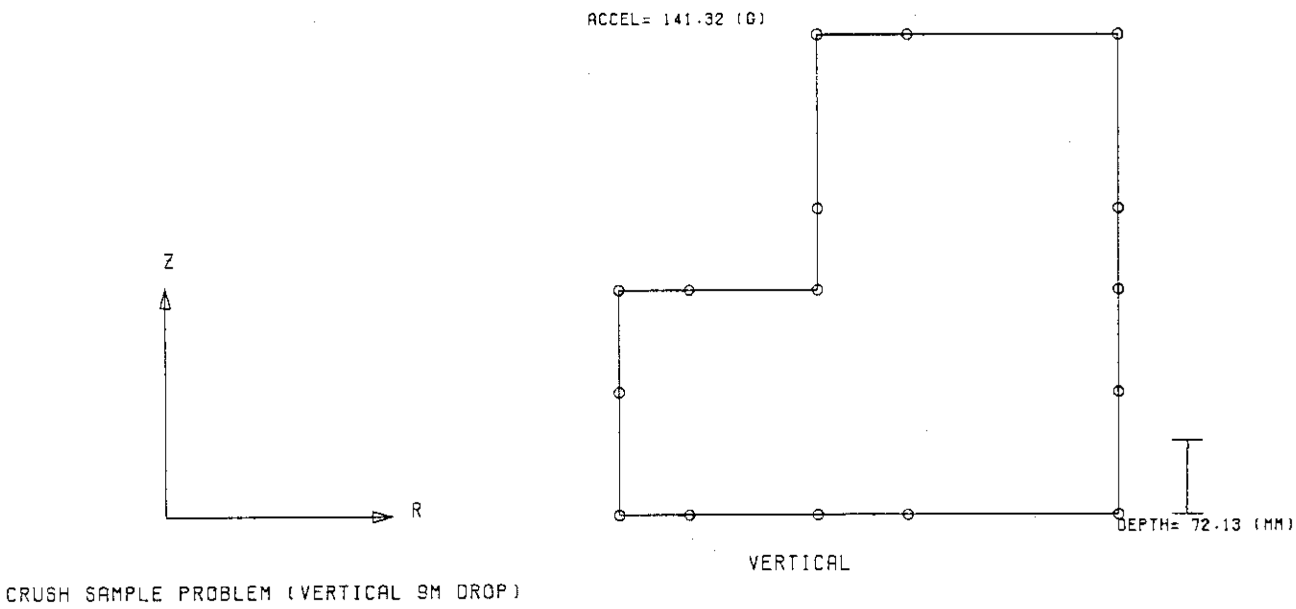

Fig. C.1 Graphical output of CRUSH(1)

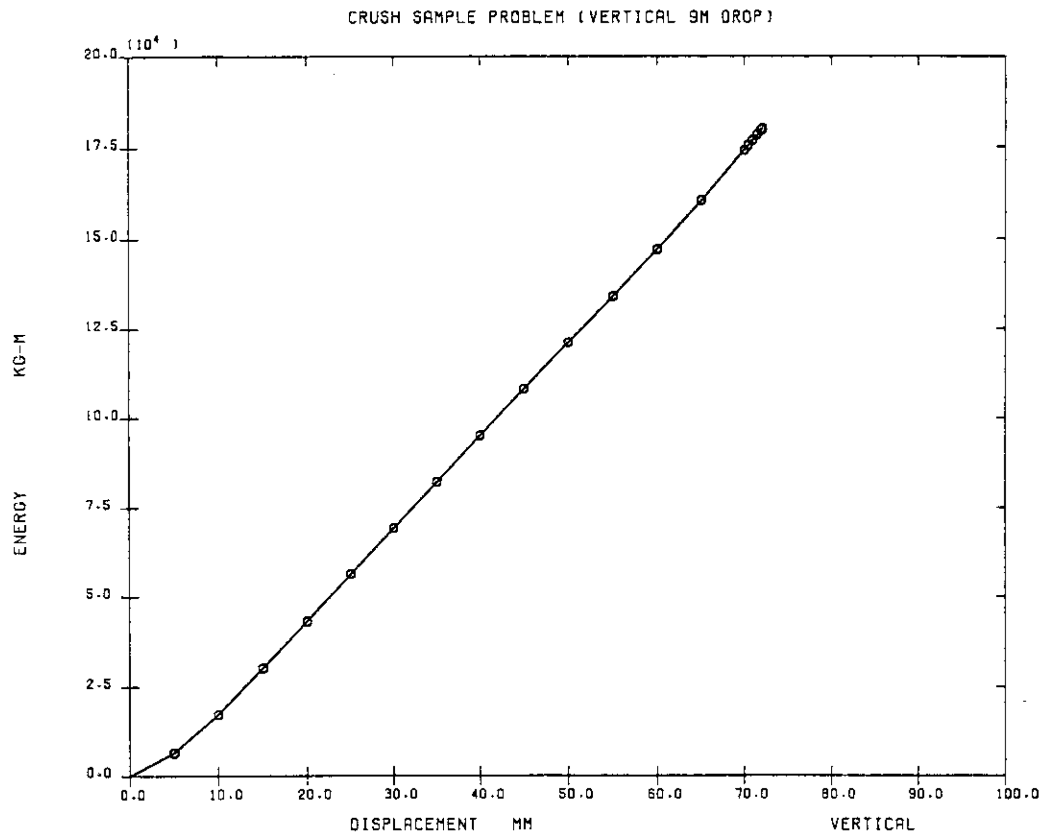

Fig. C.2 Graphical output of CRUSH(2)

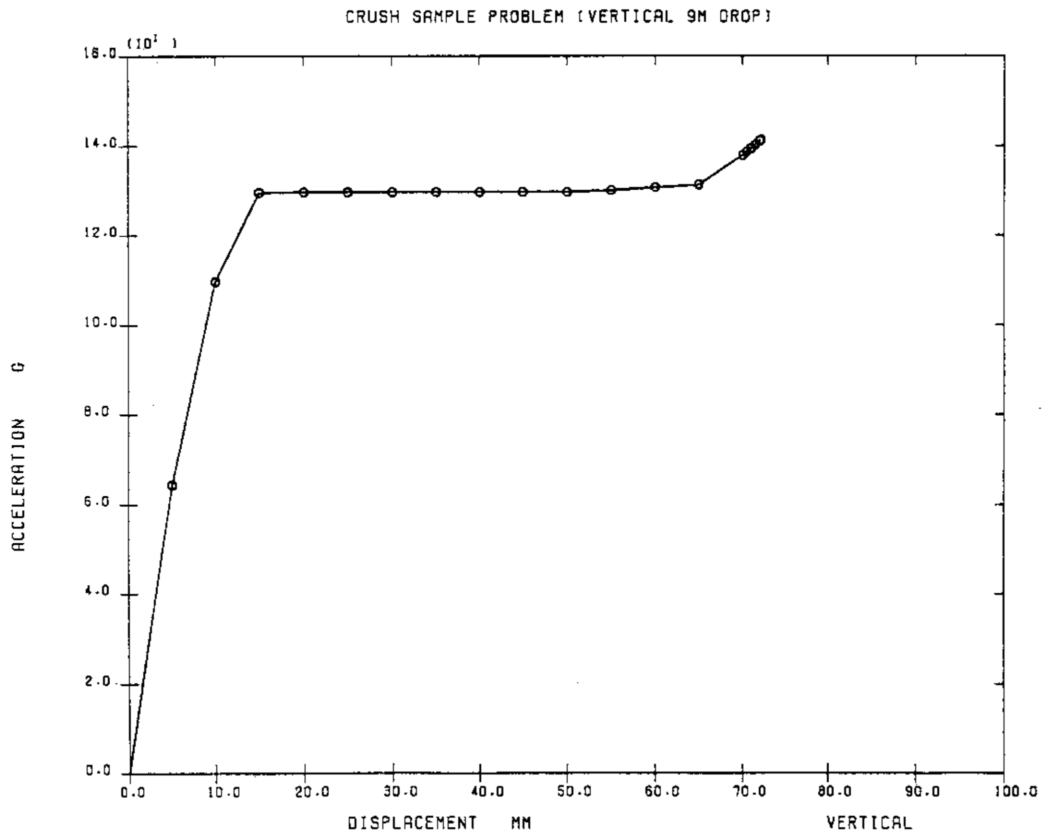

Fig. C.3 Graphical output of CRUSH(3)

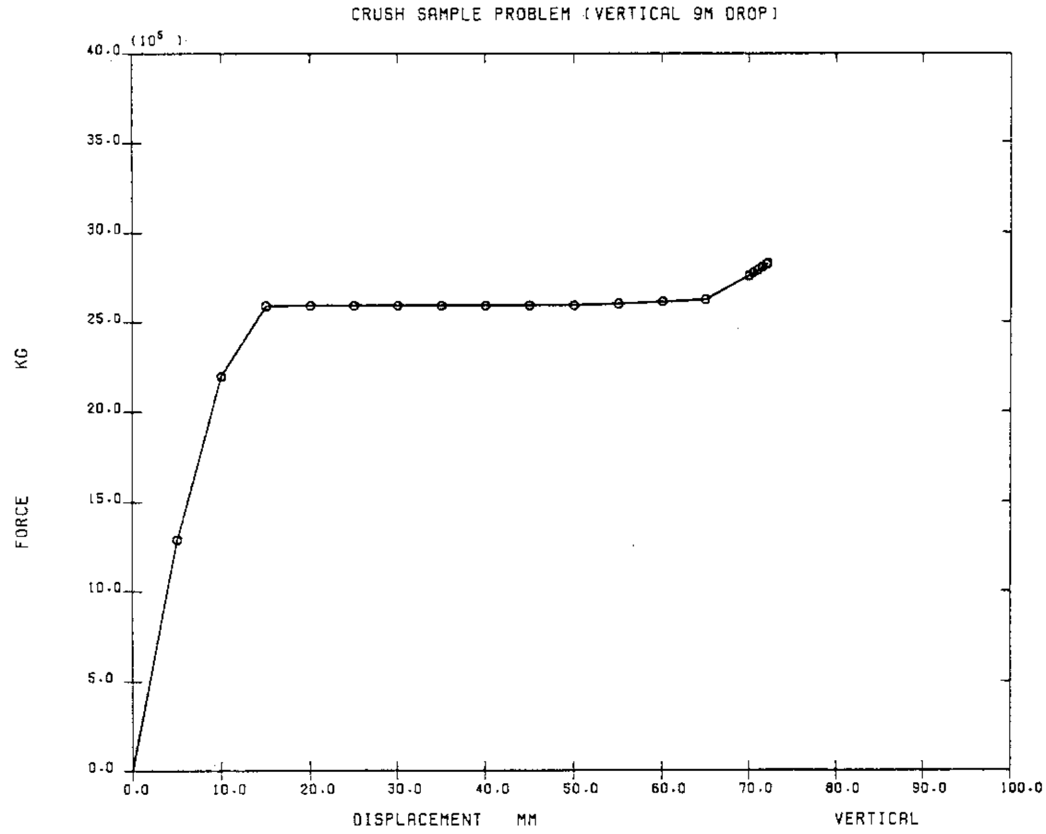

Fig. C.4 Graphical output of CRUSH(4)

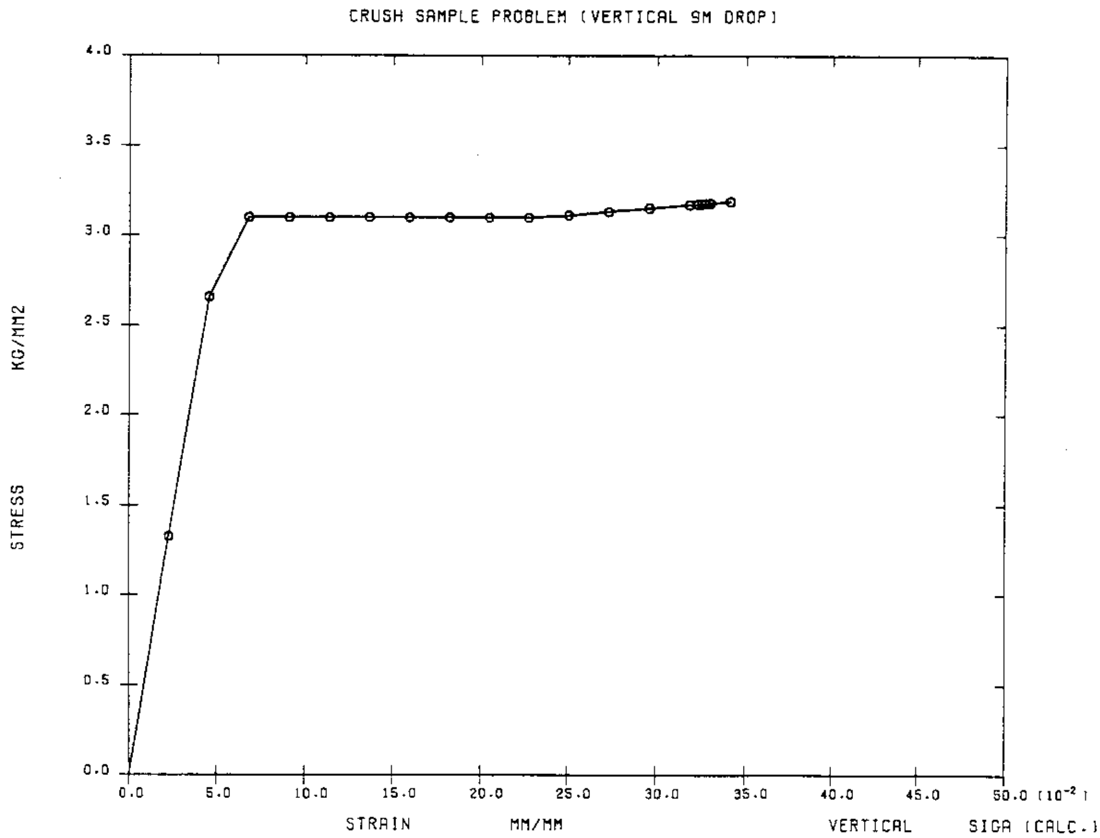

Fig. C.5 Graphical output of CRUSH(5)

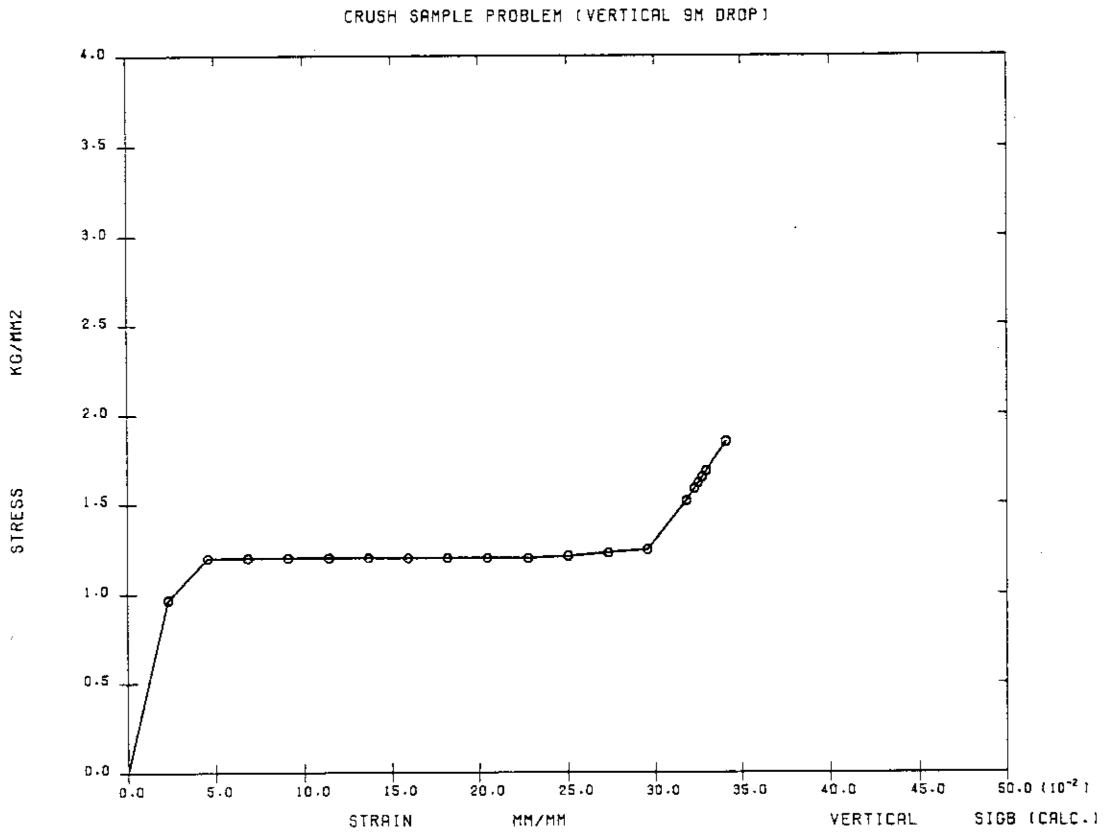

Fig. C.6 Graphical output of CRUSH(6)

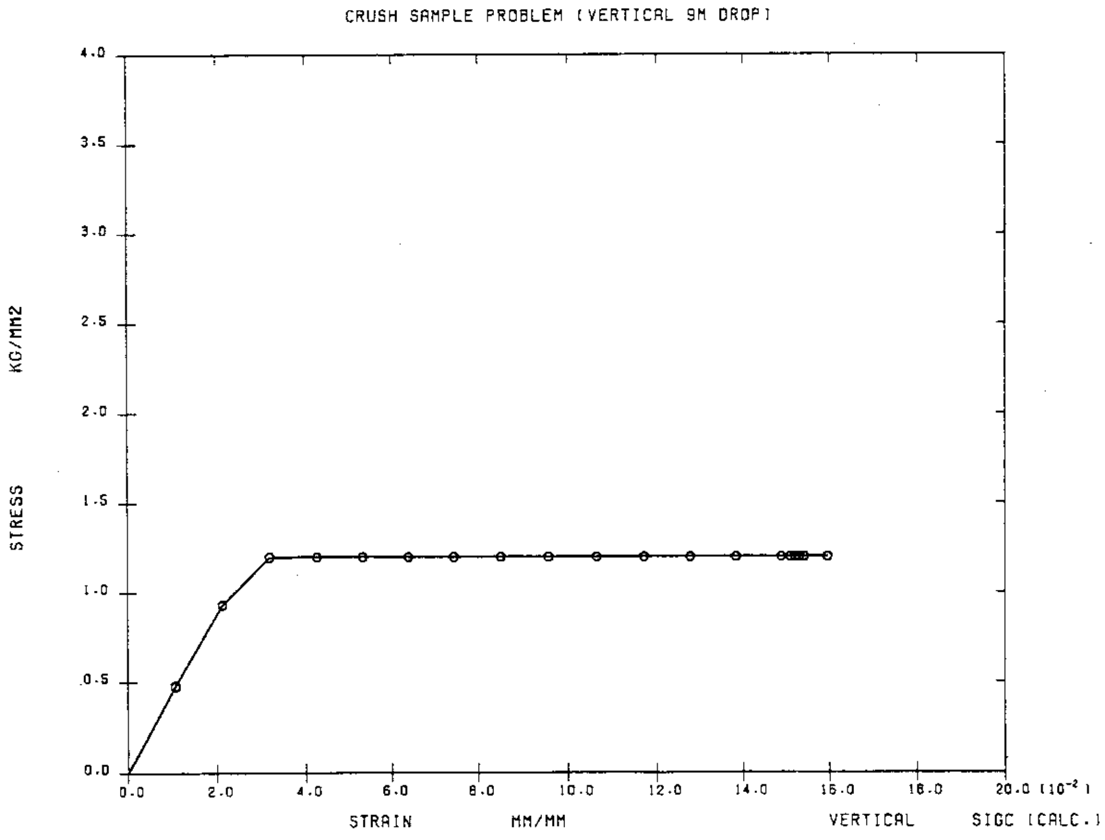

Fig. C.7 Graphical output of CRUSH(7)

Appendix D Job control data

```
//JCLG JOB
// EXEC JCLG
//SYSIN DD DATA,DLM='++'
// JUSER XXXXXXXX,XX.XXXXXXXX,XXXX.XXX,CRUSH
   T.1 C.1 W.2 I.2 CLS GRP
   OPTP PASSWORD=XXXXXXXX
//RUN EXEC LMGO,LM=JXXXX.LMCRUSH1,PNM=CRUSH1
// EXPAND  GRNLP
//FT55F001 DD DSN=JXXXX.DTCRUSH1.DATA,DISP=SHR
// EXPAND  DISK,DDN=FT02F001
++
//
```

Appendix E Program abstract in NEA DATA BANK Format

1. Name : CRUSH.
2. Computer for which the program is designed and others upon which it is possible:

   FACOM-M780, IBM-PC, NEC-PC.
3. Nature of physical problem solved:

   Drop impact analysis of radioactive material transportation casks.
4. Method of solution:

   One-dimensional static analysis.
5. Restrictions on the complexity of the problem: None.
6. Typical running time:

   FACOM-M780 : 1 ~ 2 seconds.

   IBM PC : 1 ~ 5 minutes.
7. Unusual features of the program: None.
8. Related and auxiliary program: None.
9. Status :
10. References:

    "Simplified Analysis Computer Programs and Their Adequacy for Radioactive Materials Shipping Casks", PATRAM '89 (Washington, DC, USA June 11-16, 1989).
11. Machine requirement:

    Requires 640 k bytes of core memory.
12. Program language used: FACOM-M780 FORTRAN-77.
13. Operating system or monitor under which the program is executed:

    FACOM M.

14. Any other programming or operating information or restrictions:

The program is approximately 2800 source steps. The plotting program is used for the CALCOMP plotter or the compatible ones.

15. Name and establishment of author:

T. Ikushima. Japan Atomic Energy Research Institute, Tokai Research Establishment, Tokai-mura, naka-gun, Ibaraki-ken, 319-11, Japan.

16. Material available: Source.