Failure Probability Study on Spent Fuel Transportation Cask Considering Several Key Parameters

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Abstract

There are many parameters that will affect the failure probability of the spent fuel transportation cask in a traffic accident. Especially cask collision speed with rocks or other vehicles, collision angle of the cask and the strength of the cask material are important parameters. And these key parameters are distributed probabilistically. Even only these factors are taken into consideration, there are so many cases of parameter combination that should be conducted for cask safety analysis. So, it is necessary to treat these parameters as probabilistic factors and also evaluate the total probability of cask failure with minimum cask crush analyses for estimation of the cask safety under wide ranges of traffic accident type.

In order to minimize the number of crush analyses, the response surface method has been used. The probability density function for the collision speed has been developed based on the actual accident records. And this probability function is supposed to be normally distributed around the real data distribution. The angle of cask collision is another key factor for cask deformation. Crush angle ranges from horizontal (angle 0 degree) to vertical (angle 90 degree) and the probability density of the angle is supposed to be constant. The allowable limit for the maximum cask plastic strain is assumed to be the elongation of the cask material and its probability density has been postulated to be a normal distribution. Based on these probabilistic assumptions and response surface results made from minimum crush analyses, failure probability of the cask in a traffic accident is estimated.

The response surface of the cask maximum plastic strain as a function of crush speed and angle is so complicated. Thick walled cask chosen as a typical cask for estimation has a peak failure probability density at an angle of 65.7 degree. And the probability of the cask failure in a traffic accident ranges from 0.0022% to 0.0042%. These probability values depend on cask design, crush speed and other factors. Failure probability estimation method using response surface method is effective to understand the safety of spent fuel transportation cask in a traffic accident.

1. Introduction

This paper describes an estimation method of failure probability of spent fuel transportation cask in a traffic accident. Cask failure probability will be affected by many kinds of parameters, such as:

(1) Cask collision speed with rocks or other vehicles,
(2) Collision angle of the cask,
(3) Strength of the cask material,

(4) Existence of shock absorbers,

(5) Cask design etc.

These parameters except cask design have probabilistic distribution. So, these parameters should be treated as probabilistic in order to estimate the failure probability of the cask. Cask response in collision depends on the combination of cask collision speed and angle etc. The response of the cask is so complicated that many cases of crush analysis have to be conducted changing related parameters, and it will lead to a very high computational cost. In order to avoid this problem, the response surface method is used. The purpose of this paper is to illustrate such method using response surface method for estimating the failure probability of the cask, so the cask collision speed and angle are chosen to make the response surface and the probabilistic distribution of the cask material strength is considered in the failure probability estimation.

2. Cask collision speed and angle distribution

The cask collision speed in a traffic accident is modeled based on data shown in table 2.5 of ref.1 (L.E.Fiscer et.al.). The following value “vw” is cask collision speed (km/hr) and value “cup” is cumulative percent (%). From these data, the probability density function (PDF) of collision speed is developed as the next function f(v,C). And the PFD of collision angle is assumed to be 1/90.

$$\mathrm{vw} := \begin{pmatrix} 0 \\ 5 \\ 15 \\ 25 \\ 35 \\ 45 \\ 55 \\ 65 \\ 75 \\ 85 \\ 95 \end{pmatrix} \cdot 1.6 \qquad \mathrm{cup} := \begin{pmatrix} 0 \\ 33.79 \\ 54.35 \\ 72.47 \\ 85.5 \\ 94.84 \\ 98.37 \\ 99.38 \\ 99.94 \\ 99.98 \\ 100 \end{pmatrix}$$

$$f(v,C) := \frac{\left[\frac{kr_0}{C} \cdot \left(\exp\left(\frac{-v}{C}\right) - \exp\left(\frac{-V0}{C}\right)\right)\right]}{\int_0^{V0} \frac{kr_0}{C} \cdot \left(\exp\left(\frac{-v}{C}\right) - \exp\left(\frac{-V0}{C}\right)\right) dv}$$

$$kr_0 = 97.032$$

In the above function f(v,C), the value “V0” is the maximum speed value 160 km/hr and “C” is the normal distribution parameter for uncertainty of the collision speed distribution pattern. The mean value of “C” is 29.153 and its standard derivation is assumed to be 2.0.

The collision speed PDF functions and cumulative percent curves are shown in Fig. 1.The values PVP and GGP correspond to the 95% confident upper bound value “CP=33.073” and PVN and GGN correspond to the lower bound value “CN=25.233”. And PV and GG values correspond to mean “C” value “cm”. And dot points in the cumulative percent curve are input data points. The PDF of “C” parameter is expressed by the following function PC(C).

$$\mathrm{cm} = 29.153 \qquad \mathrm{cs} := 2 \qquad PC(C) := \frac{1}{\sqrt{2 \cdot \pi} \cdot \mathrm{cs}} \cdot e^{\frac{-(C-\mathrm{cm})^2}{2 \cdot \mathrm{cs}^2}}$$

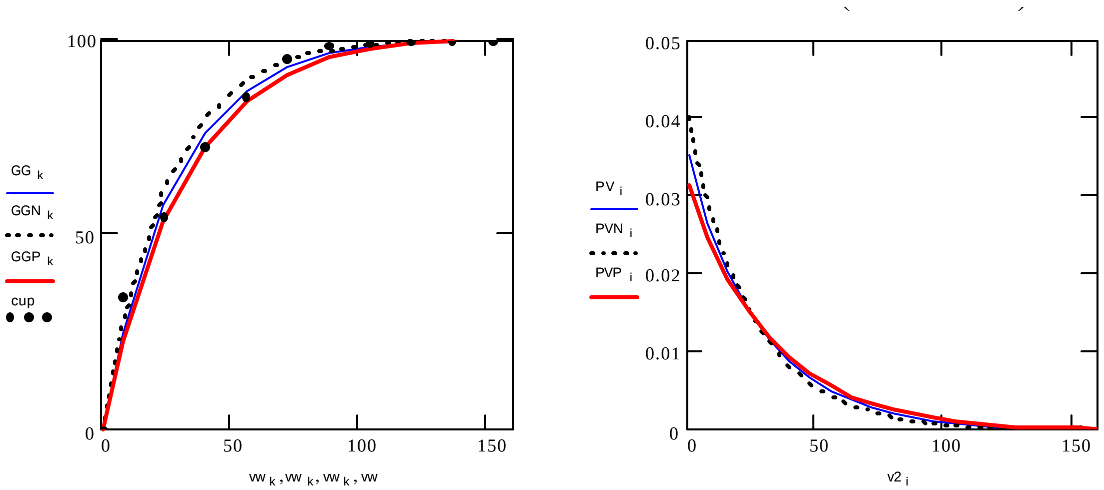
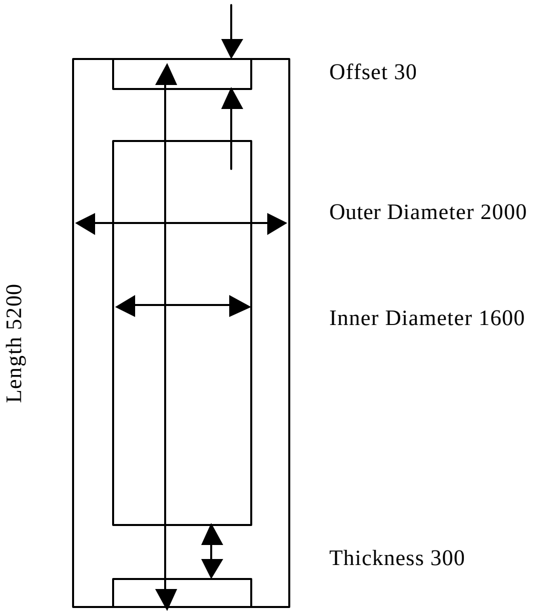


Fig.1 Cumulative percent curve (left) and collision speed PDF functions (right).

3. Response surface of cask deformation

The simplified crash analysis model of the cask is shown in Fig.2.



Cask material : SUS304
Elastic modulus : 19400kg/mm^2
Hardening modulus : 140 kg/mm^2
Poisson's ratio : 0.29
Yield stress : 17.6 kg/mm^2
Density : 8 x 10^{-6}kg/mm^3
Cask weight : 80 tons

Fig.2 Crash analysis model of the cask

Crash analyses are conducted for 20 cases changing crash speed and collision angle. The maximum effective plastic strain values of the cask boundary in each case are shown in Table 1.

In Fig.3 to 5, the results by LS-DYNA for collision angle 67.5 degree and collision speed 160 km/hr are shown as typical analysis results.

Table1 Crash analysis results by LS-DYNA

Angle(deg)	Speed			
	40km/hr	80km/hr	120km/hr	160km/hr
0	11.5%	19.9%	25.6%	31.0%
22.5	1.8%	14.0%	21.0%	22.3%
45	6.4%	16.6%	27.6%	39.5%
67.5	17.4%	25.2%	30.0%	35.5%
90	3.7%	8.9%	12.7%	15.8

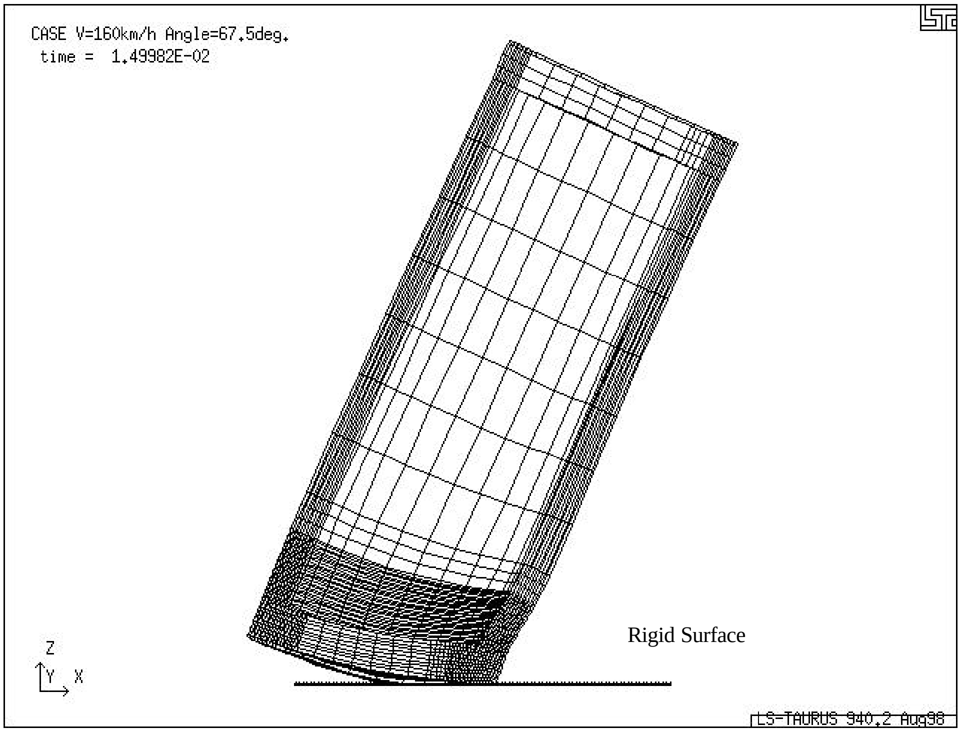


Fig.3 Deformation of the cask (15.0 msec)

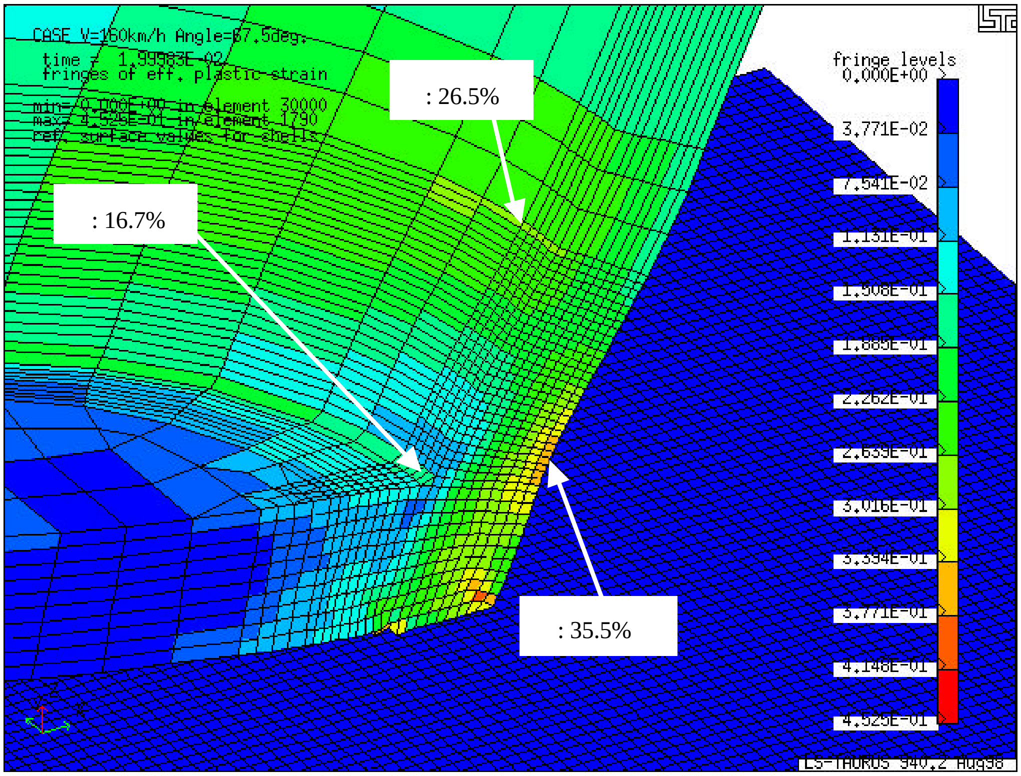


Fig.4 Distribution of the equivalent plastic strain

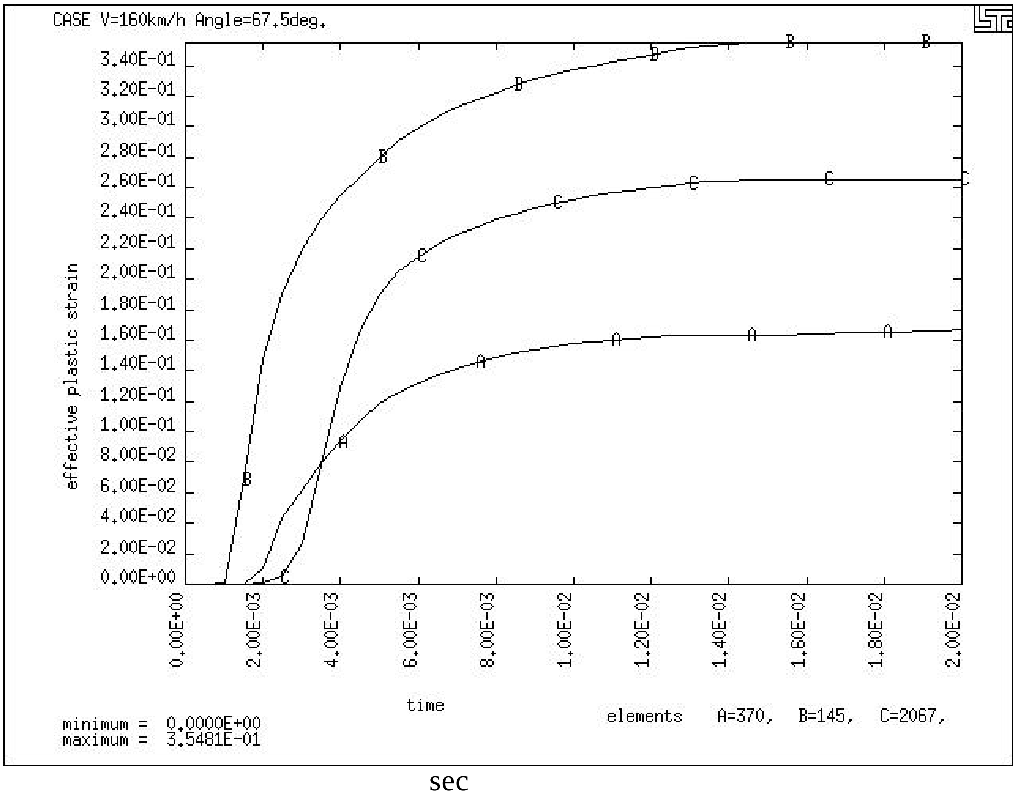
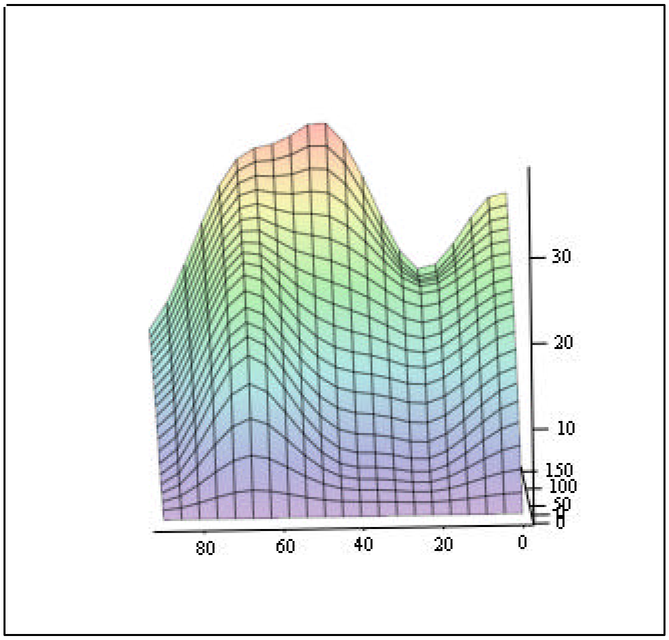


Fig.5 Time history of the equivalent plastic strain

Based on crash analysis results by LS-DYNA shown in Table1, the response surface for maximum effective plastic strain of the cask boundary wall is made. The resulting response surface is shown in Fig.6. This response surface is fixed by 20 crash analysis data using spline interpolation method. The analysis data for 22.5 degree and 40km/hr is conservatively changed from 1.8% to 5% to avoid undershoot in spline interpolation, which cause the negative effective strain region in the response surface. The maximum plastic strain as a function of collision speed and angle can be expressed by a function RL(v,t) , where "v" is collision speed and "t" is collision angle.



Horizontal direction : Collision angle (deg)
Depth direction : Collision speed (km/hr)
Vertical direction : Maximum plastic strain response in the cask wall boundary (%)

(V ,T ,FF1)

Fig.6 Response surface of the cask deformation

4. Allowable plastic strain limit

Allowable strain limit has also probabilistic distribution. In this study mean elongation value is assumed to be 63% and the 95% confident lower bound elongation value is set to be 40%. And its distribution is supposed to be normal, so the PFD of the allowable strain limit is expressed by the next function EL(z).

$$m1 = 63 \qquad s1 = 11.75 \qquad EL(z) := \frac{e^{-\frac{(z-m1)^2}{2 \cdot s1^2}}}{\sqrt{2 \cdot \pi} \cdot s1}$$

5. Failure probability evaluation

In this study, it is assumed that failure of the crashed cask occurs at the location where the maximum response plastic strain RL(v,t) exceeds the allowable strain limit "z". So, new variable "u" which is defined by next equation is introduced.

$$u := z - RL(v,t)$$

When the value “C” and “t” are some constant value “CX” and “TX”, the failure probability of the cask is calculated by the next equation, integrating by “u” from low enough value up to 0. If integration by “u” is carried out for enough wide range, the integrated value becomes 1.0.

$$\mathrm{TX} := 67.5 \qquad \mathrm{CX} = 29.153 \qquad \int_{-20}^{0}\int_{0}^{160} \mathrm{EL}\left(u + \mathrm{RL}(v, \mathrm{TX})\right)\cdot f(v, \mathrm{CX})\, dv\, du = 0.00011713$$

$$\int_{-20}^{100}\int_{0}^{160} \mathrm{EL}\left(u + \mathrm{RL}(v, \mathrm{TX})\right)\cdot f(v, \mathrm{CX})\, dv\, du = 1.000$$

The failure probability for the unit angle as a function of collision angle “T” and parameter “C” can be evaluated by the following equation.

$$\mathrm{hww}(T, C) := \int_{-20}^{0}\int_{0}^{160} \mathrm{EL}\left(u + \mathrm{RL}(v, T)\right)\cdot f(v, C)\cdot \frac{1}{90}\, dv\, du$$

The function hww(T,C) is plotted against angle “T” in Fig.4. And “HW” curve corresponds to mean “C” value “cm”. The other “HWN” and “HWP” curves correspond to the 95% confident lower and upper bound value of “C”. From these results, it is found that failure rate increases as the parameter “C” increases.

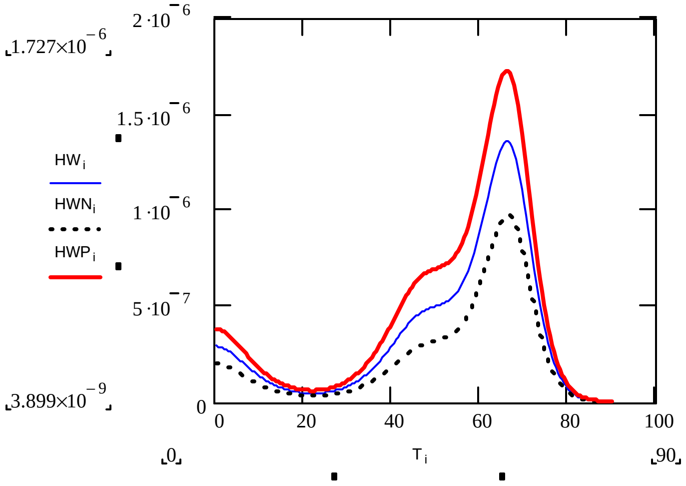


Fig.4. Failure probability of cask as a function of collision angle.

The failure probability range corresponding to the values of “CP” and “CN” is obtained by integrating above “hww(T,C)” by angle and the range becomes from 0.0022% to 0.0042%.

$$\mathrm{CN} = 25.233 \qquad \int_{-20}^{0}\int_{0}^{90}\int_{0}^{160} \mathrm{EL}\left(u + \mathrm{RL}(v, t)\right)\cdot f(v, \mathrm{CN})\cdot \frac{1}{90}\, dv\, dt\, du = 0.00002222$$

$$CP = 33.073 \qquad \int_{-20}^{0}\int_{0}^{90}\int_{0}^{160} EL(u + RL(v,t)) \cdot f(v,CP) \cdot \frac{1}{90}\, dv\, dt\, du = 0.00004228$$

As “C” is a probabilistic variable, the failure probability of the cask in an accident is finally calculated by the next equation. In this equation, integration by “C” is conducted for wide enough range of variable “C”. And the failure probability becomes 0.0032%.

$$\int_{-20}^{0}\int_{0}^{90}\int_{10}^{50}\int_{0}^{160} EL(u + RL(v,t)) \cdot f(v,C) \cdot PC(C) \cdot \frac{1}{90}\, dv\, dC\, dt\, du = 0.00003216$$

In order to check the above equation, integration over the whole region is done as follows and the result becomes 1.0.

$$\int_{-20}^{100}\int_{0}^{90}\int_{10}^{50}\int_{0}^{160} EL(u + RL(v,t)) \cdot f(v,C) \cdot PC(C) \cdot \frac{1}{90}\, dv\, dC\, dt\, du = 1.000$$

6. Conclusion

The main aim of this study is to illustrate that the use of response surface method is useful to estimate the failure probability of the spent fuel trans potation cask. Still there are problems to be refined, the application of the response surface method to the evaluation of the failure probability of the cask is found to be effective. In this study, the maximum effective plastic strain data by LS-DYNA are chosen for the response result and from these response data, response function as a function of collision angle and speed is made and utilized to estimate the failure probability.

7. References

(1) Fischer L,E. et al “Shipping Container Response to Severe Highway and Railway Accident Conditions Vol.1 & 2”, NRC,NUREG/CR-4829, Apr.1987

(2) Shiratori M. et al “Optimization of Nonlinear Problems using Experimental Design Method”, Asakura Co.,ISBN4-254-11487-7, 1998 (In Japanese)