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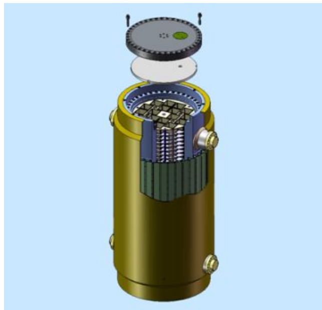
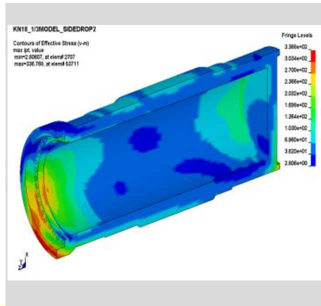
Validation of Numerical Simulation Method Using a 1/3-Scale Model Drop Test of KN-18 SNF Transport Cask

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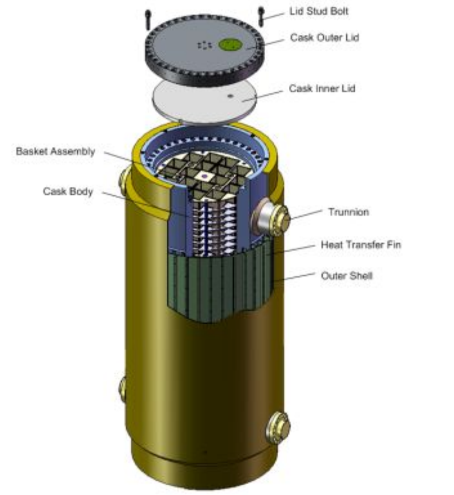
Contents

1. Introduction

◆ BACKGROUND

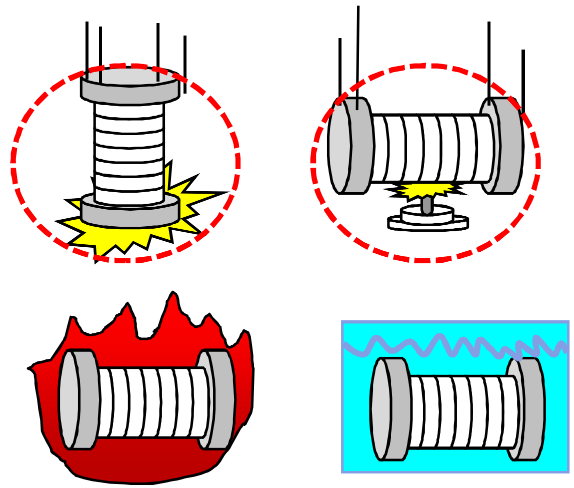
- KN-18 is a newly developed SNF transport cask in South Korea by KHNP and KONES *(for 18 PWR)* (▹)
- Regulations for SNF transport cask
  :9m drop, 1m puncture, 800℃ fire, 200m immersion (▹)
- *Two types of method for integrity assessment : Numerical simulation using FE-method, Actual test*
- Structural performance of KN-18 was demonstrated in the SAR by the analysis using state-of-the-art FE-methods via LS-DYNA(another paper)



[KN-18 SNF Transport Cask]

◆ OBJECTIVE

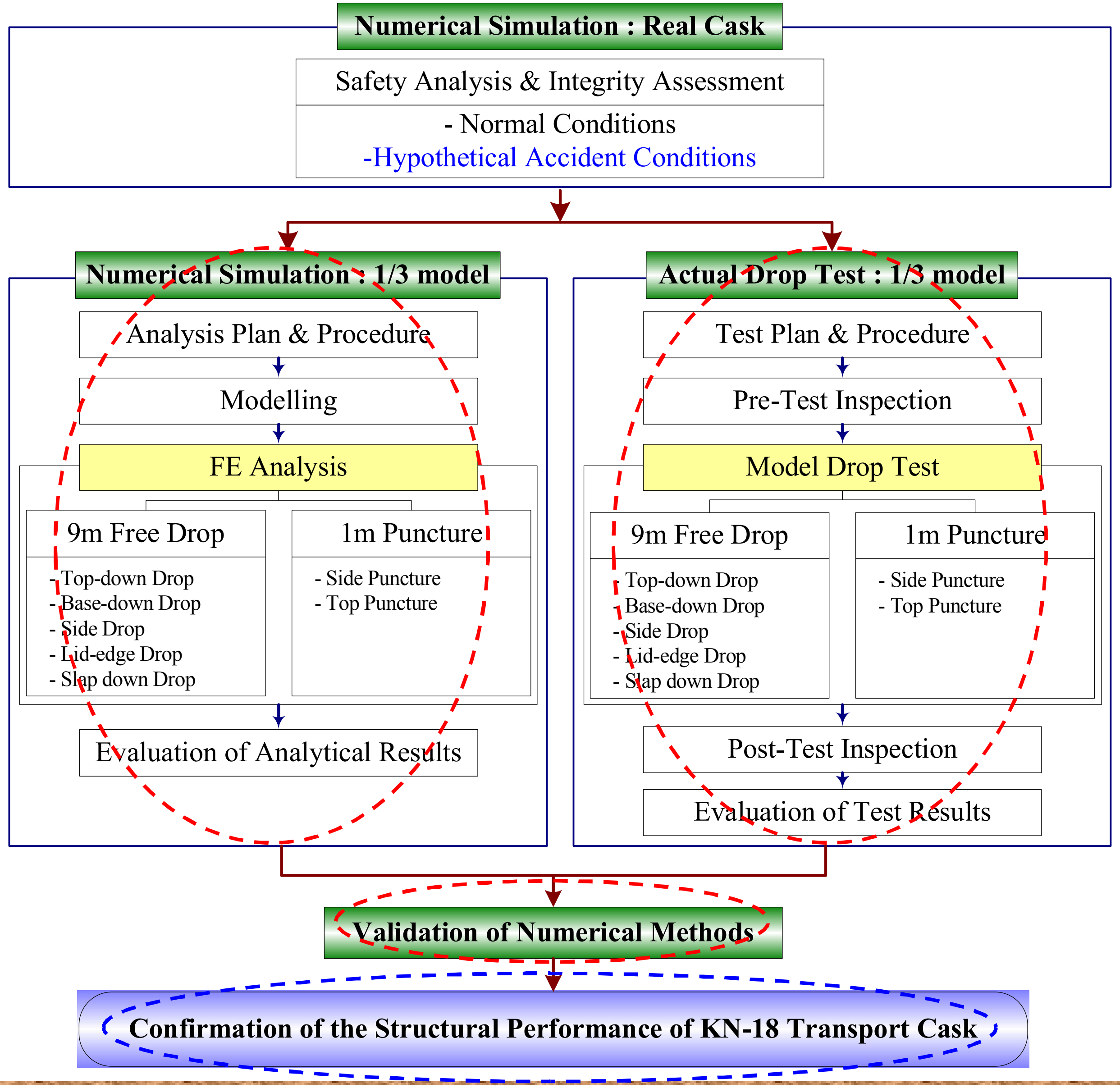
- A series of actual drop tests using 1/3-scale model
- FE-analyses of the scale model cask in all the drop test conditions (same numerical method)
- This paper presents the dynamic impact characteristics of the cask from test and analysis results
- The validation of numerical simulation method used in the analyses by showing the correlation between test and analysis results



[Regulations]

1. Introduction

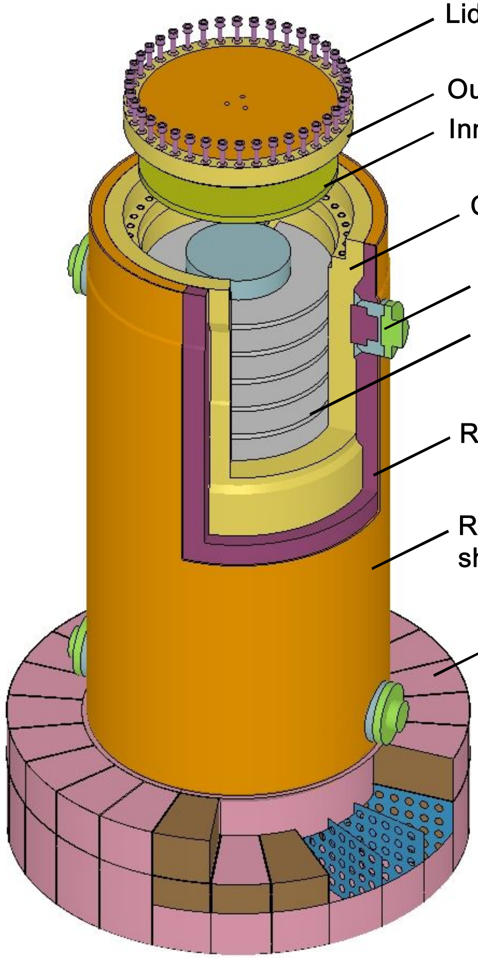
[Scope & Flowchart]



◆ Scale Model Design

- Scale down original KN-18 by factor of 3
- Basically, same design as a real cask
- (▹) Overview of scale model
- (▹) Consist of cask body, outer & inner lid, lid bolt, resin, resin-shell, basket dummy, trunnion(2 set)
- (▹) 2 Impact limiter *: Beech & spruce, housing, gusset*
- Overall size : Length(2.101m), Diameter(0.782m)
- Total weight : 4.60 ton (with 2 IL)
- Material property (steel) (▿)

Material	A-350 LF3	A-182 GR.F6NM	A-240 TP304	A-453 GR.651
Components	Cask Body	Cask Lid	Resin-shell	Lid Bolt
Elastic Modulus (MPa)	1.91E05	2.01E05	1.95E05	1.95E05
Poisson Ratio	0.31	0.29	0.29	0.29
Yield Stress(MPa)	341.5	765.7	255.0	485.0
Tensile Stress(MPa)	571.1	890.4	609.0	990.0
Density (ton/mm^3)	7.62E-9	7.81E-9	8.00E-9	8.00E-9
ETAN(Mpa)	1423.6	1594.0	1550.5	3265.1



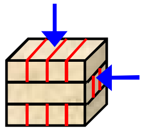
[1/3-scale model]

FABRICATION

- Fabrication process

  : (▷) cask body->cask lid->resin pouring -> basket dummy->IL housing & gusset-> insertion of wood layer

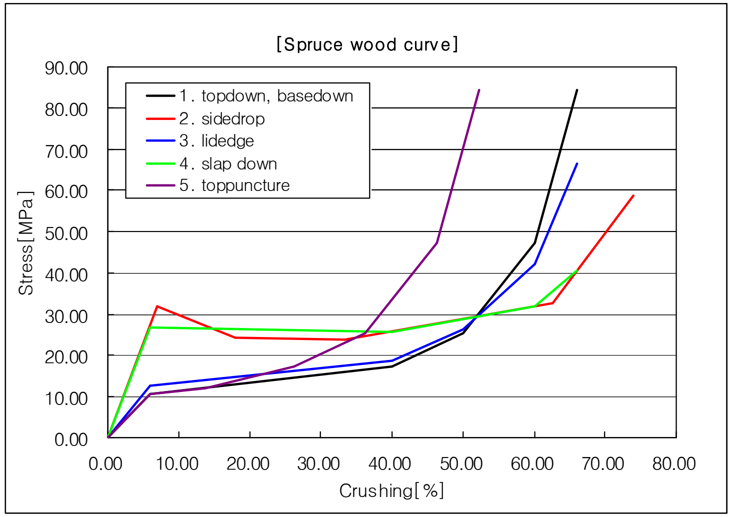
WOOD PROPERTY



- (▽)Wood crush characteristics (FE-input)

  - stress-strain behavior(test data)

  - MAT_HONEYCOMB in LS-DYNA



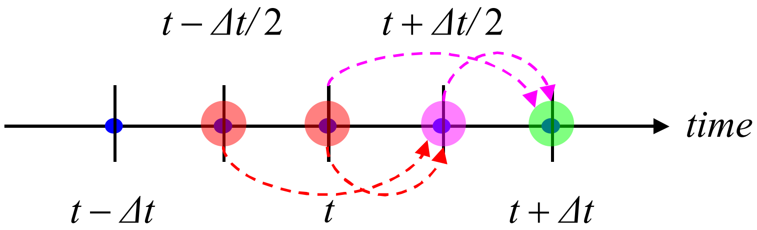
[Wood crush characteristics]

[Fabrication of the test model]

3. Outline of Numerical Analysis

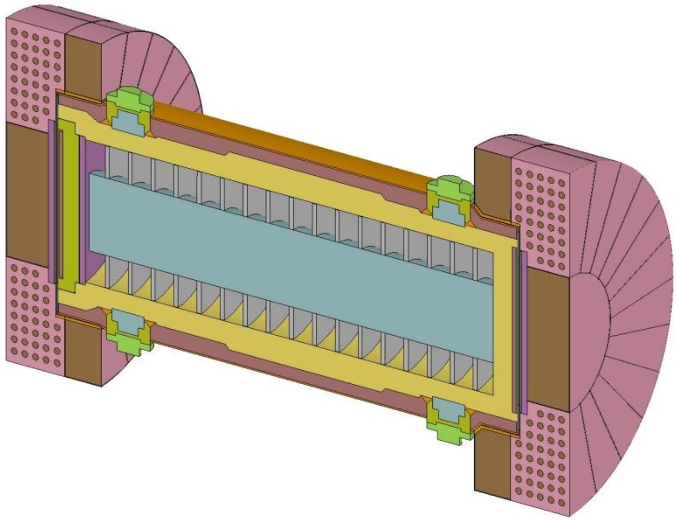
ANALYSIS METHOD

- 3D nonlinear dynamic FE-simulation
- FE Code : LS-DYNA explicit v. 970
- Explicit time integration method

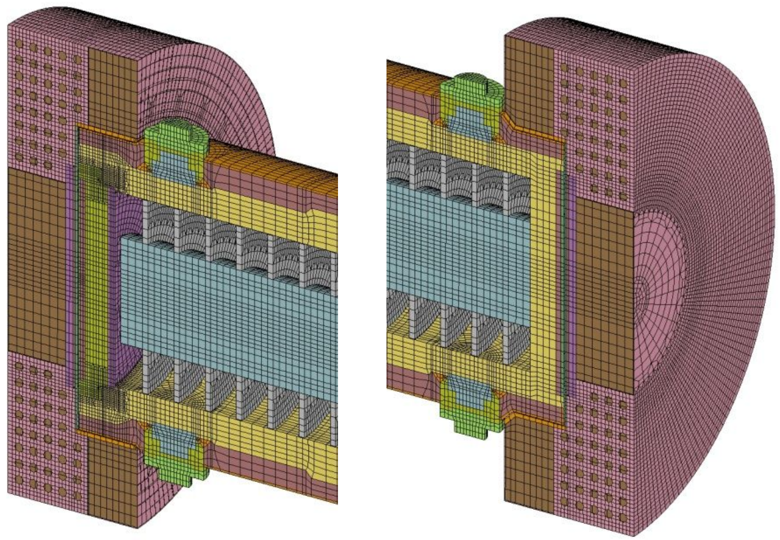


- *Velocity and displacements at time t+Δt updated explicitly*
- *Solution is trivial : diagonal mass matrix, no iteration is required*
- Ideal method for high speed impact simulation
- *Usually more reliable for problems involving discontinuous nonlinearities (Contact, Impact)*
- *Limited time increment size -> Automatic*

$$\Delta t_{min} \le \frac{2}{\omega_{max}}\left(\sqrt{1+\xi^2}-\xi\right)$$



(▹)[Overall view of the FE-model]

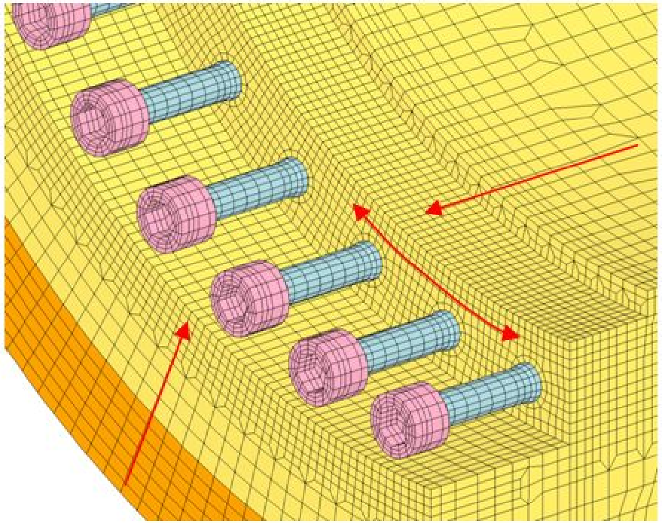


[Mesh of the FE model]

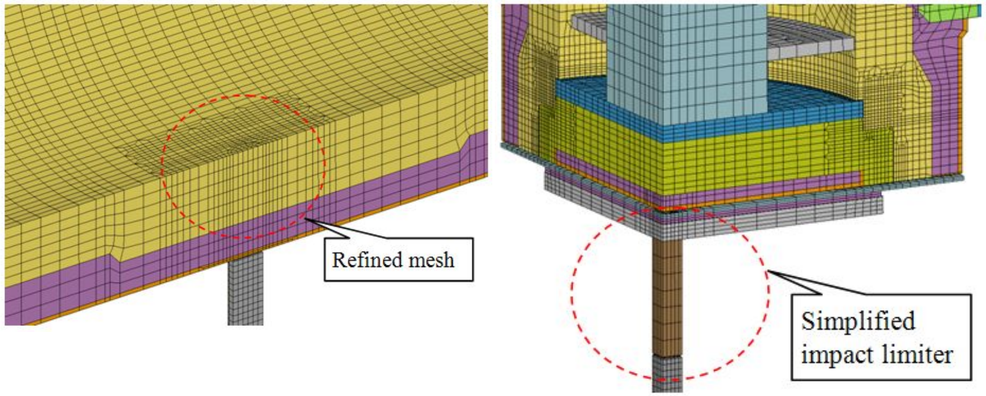
3. Outline of Numerical Analysis

◈ FE-MODELING

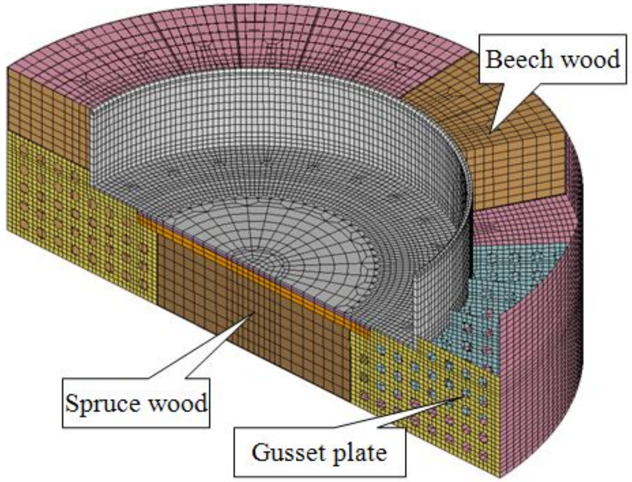
- 3D detailed FE-model
  - All components are modeled explicitly
  - *Only hexahedral solid, rectangular shell*
- Basic half symmetry model
  : 445,506 nodes, 369,182 elements
- Mesh density design
  : Purpose of analysis, package behavior
- *Fully integration solid element : Thin wall*
- *Puncture model : modification of basic model*
- *Material behavior : tri-linear elasto-plastic (steel)*



[Details at the lid-body interface]



[Details of the puncture model]



[Details of the impact limiter]

3. Outline of Numerical Analysis

[Analytical assumption]

◆ INITIAL & BOUNDARY CONDITION

➢ Two phases analysis

- Bolt pre force : dynamic relaxation phase
- Drop analysis : transient phase
- The stress at the end of the dynamic relaxation phase are carried over to become the initial stress of transient phase (▹)

➢ Initial velocity : 13.3m/s(9m), 4.43m/s(1m)

- *Model is located close to the target*

➢ *B/C : Fix(target , bar), Symmetry condition*

◆ OTHER ASSUMPTIONS

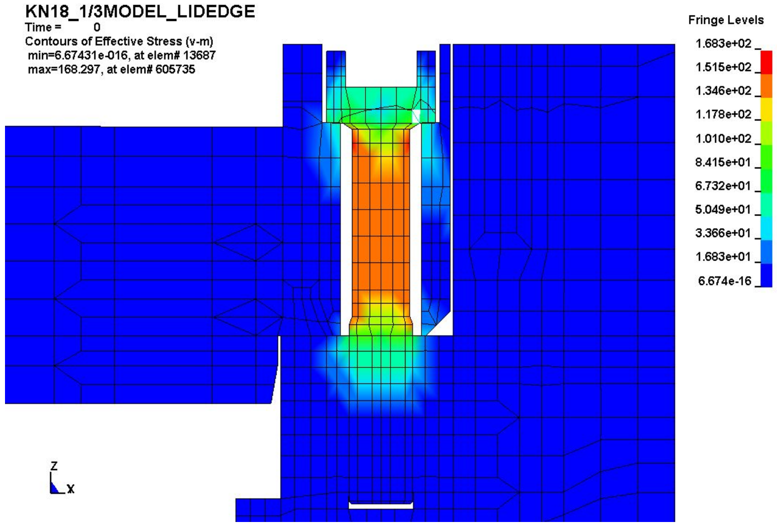
➢ Unyielding target : "RIGIDWALL" in LS-DYNA

- *no penetration and no energy absorption*

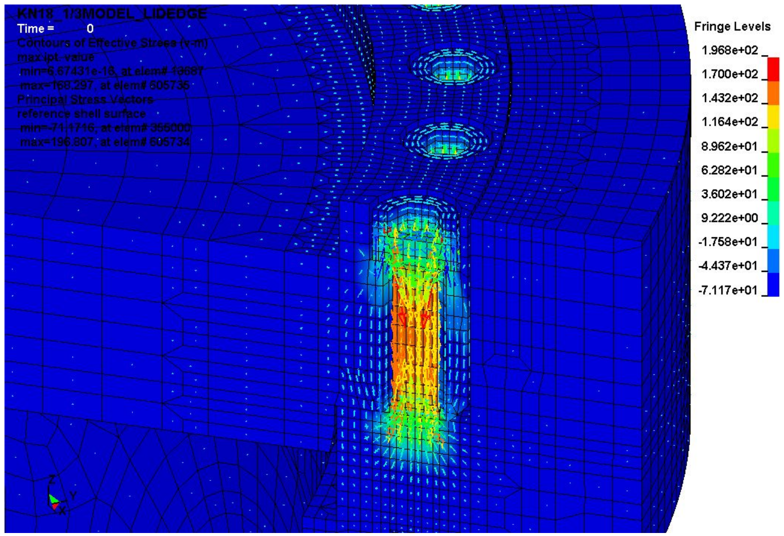
➢ *Nominal dimension in room temperature*

➢ *Contact condition : Penalty method(no friction)*

➢ *Non impacting IL removed(as in the test model)*



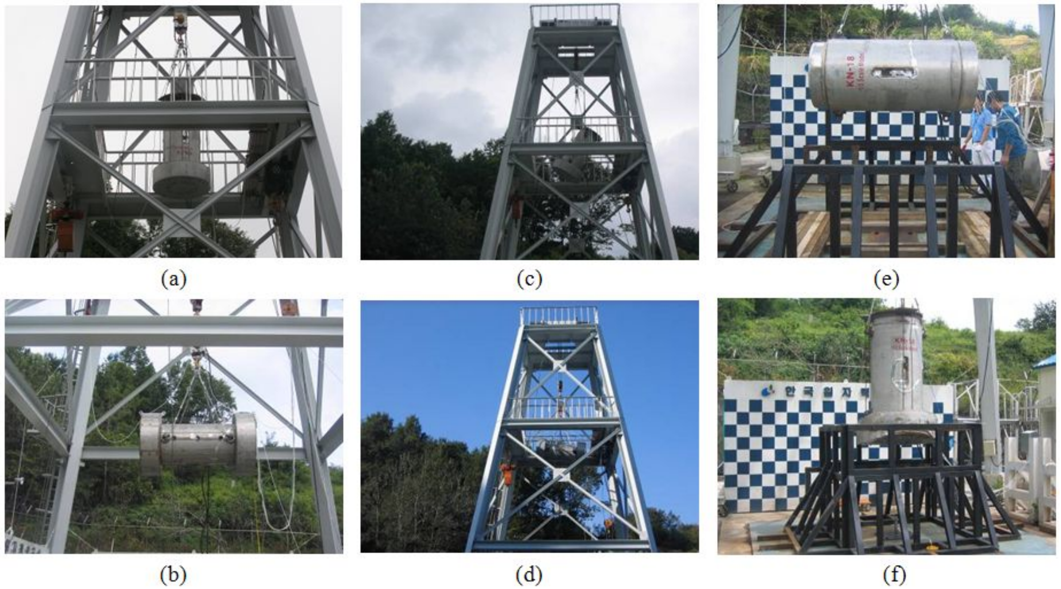
[Stress distribution due to bolt pre stress]



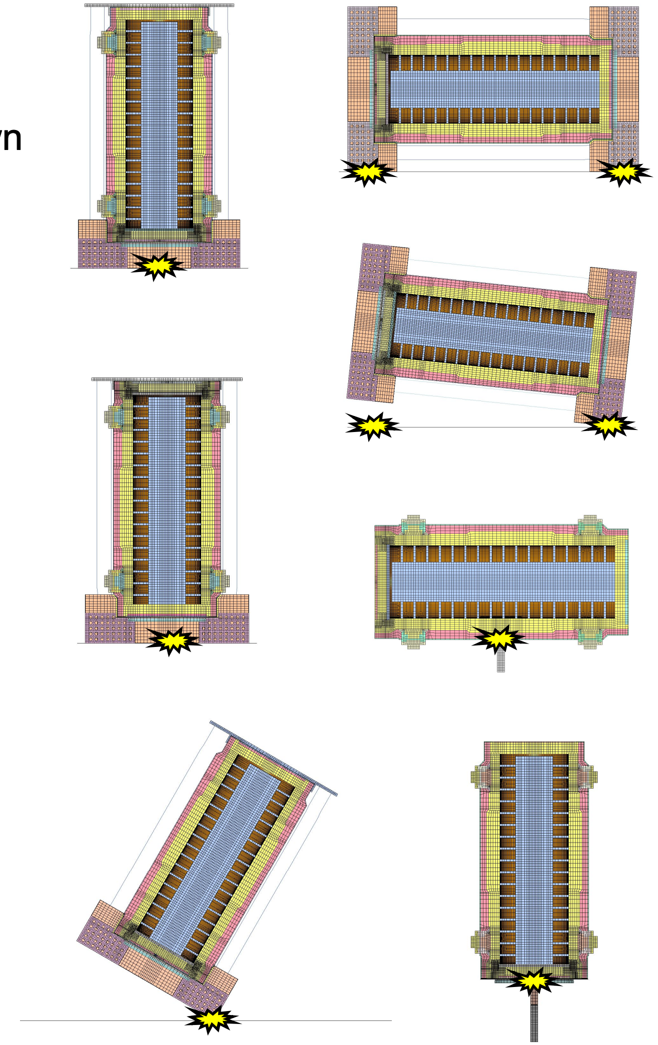
[Principal stress after dynamic relaxation]

◆ DROP ORIENTATION

- **Total 7case** : to consider worst drop orientation (▹)
  - 9m drop : top-down, base-down, side, lid-edge, slap-down
  - 1m drop : side puncture, top puncture
- **Centrally positioned** at the initial stage
- **CG** is directly over the initial impact point except for slap-down drop case
- (▿) **Initial set-up** of the test model



[Initial set-up : test model]



[Drop orientation : FE-model]

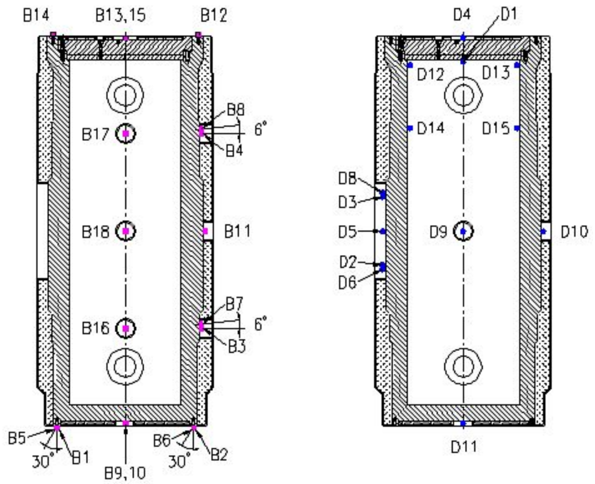
4. Outline of 1/3 Scale Model Test

◆ TEST AIM

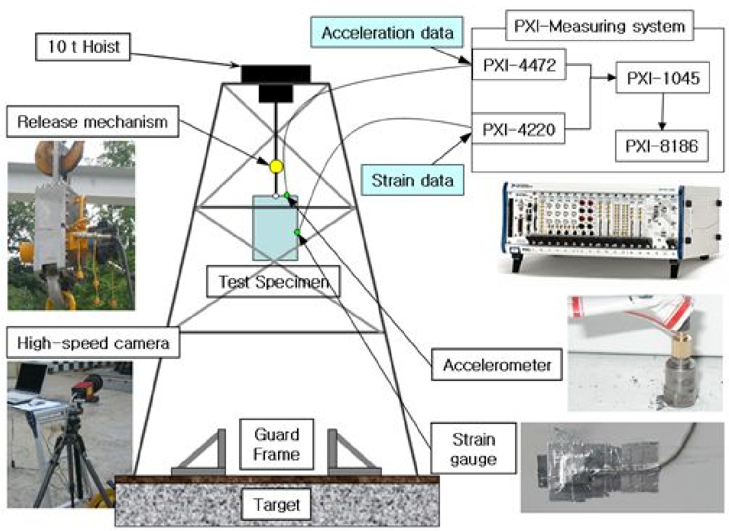
- ➢ To confirm the dynamic impact characteristics of the KN-18 transport cask
- ➢ To verify the numerical simulation method used in the analyses

◆ TEST FACILITY

- ➢ (▹) Drop test facility
  - *drop tower, unyielding target, 10t hoist, release mechanism, guard frame*
- ➢ *Measurement system*
  - (▹) strain gauges, acceleration sensors
  - *high speed camera*
  - *dynamic data acquisition system*
- ➢ (▹) Measurement point
  - base on the pre-test analysis results
- ➢ Before and after each test
  - IL deformation, cask dimensions, bolt torque are also measured



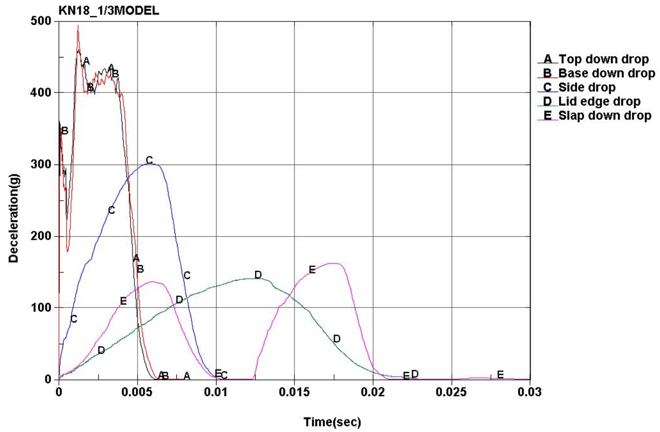
[Measurement point]



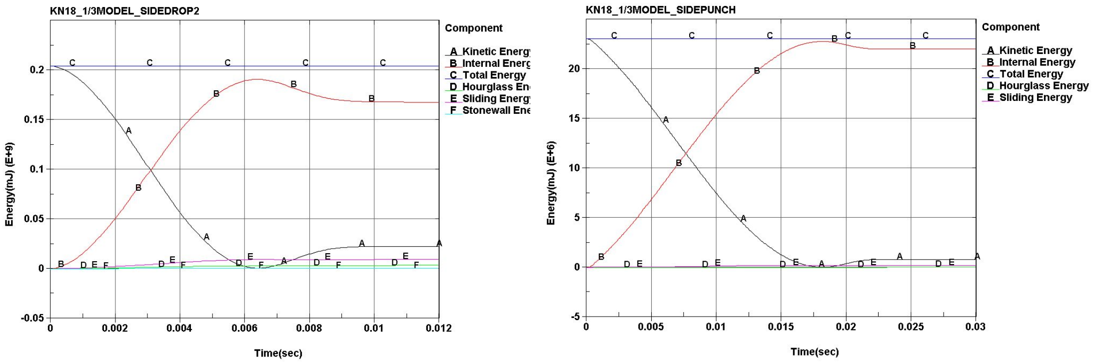
[Drop test facility and equipment]

◆ OVERALL IMPACT BEHAVIOR

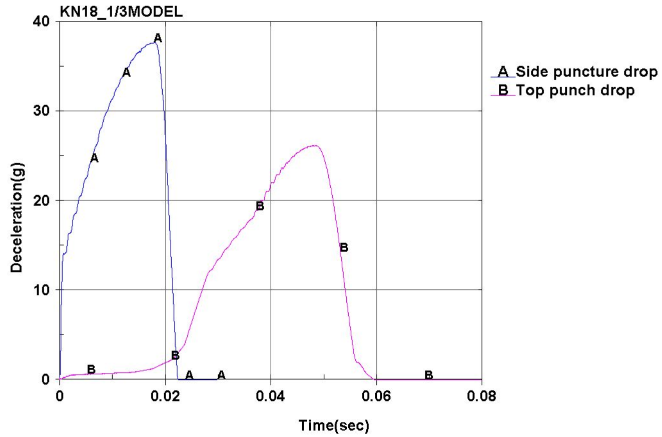
- (▿) Evaluation of energy balance
  - *energy value, smoothness, energy loss, total energy*
  - it was confirmed that the analyses were performed successfully
- (▹) Overall deceleration
  - dividing reaction force by total mass
  - max. value (9m): 141g*(lid edge)*~494g*(base-down)*
  - max. value (1m): 26g*(top)*~38g*(side)*
  - *slap-down : 2 peak, first impact < second impact*



[Overall deceleration time-history(9m)]



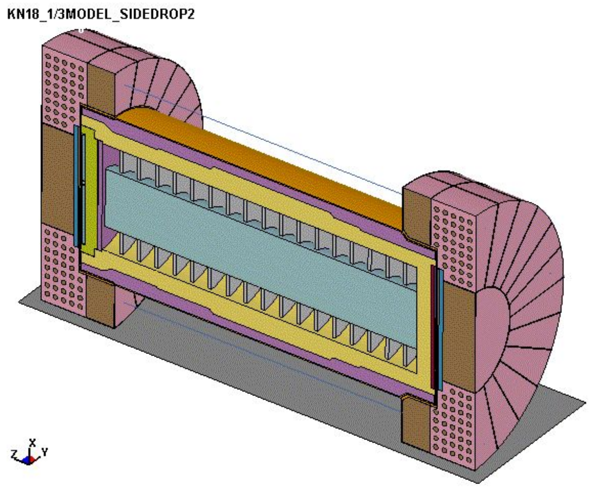
[Energy time-history]



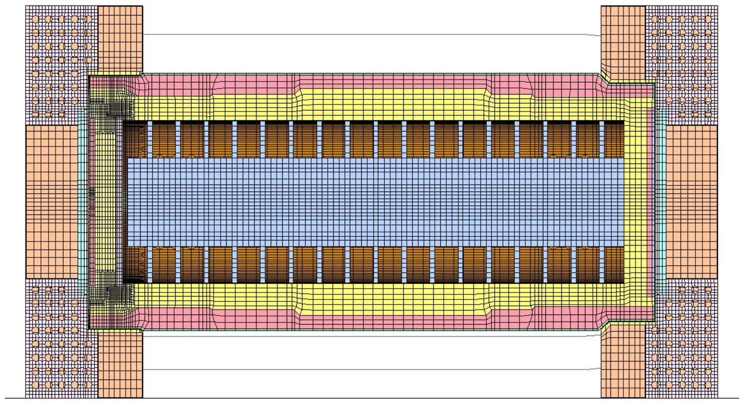
[Overall deceleration time-history(1m)]

◆ IMPACT BEHAVIOR : 9m side drop

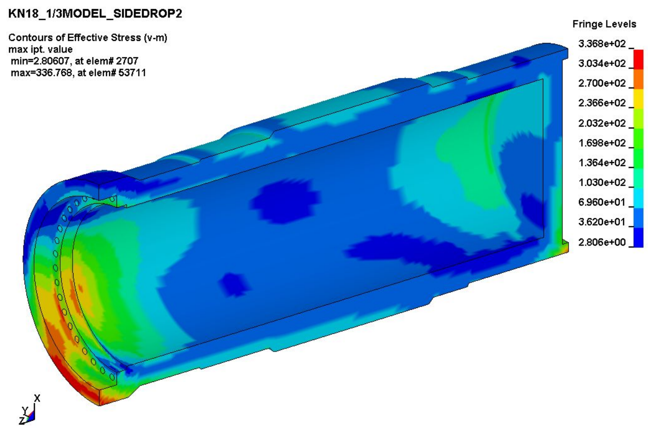
- (▿)Drop orientation at the initial stage
  - free drop on unyielding target
  - axis horizontal orientation about the target
- (▹)Drop simulation results
- Cask deflected like a simple beam supported at the top and bottom ends
  - *tensile stress on the side closest to target*
  - *compression stress on the opposite side*
- (▹)Stress distribution of the cask body
  - high stress at the top end of the cask was caused by oval deflection behavior



[Drop animation]



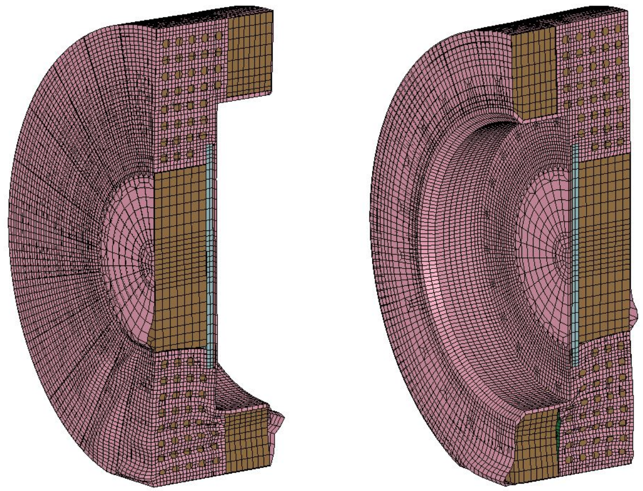
[Drop orientation]



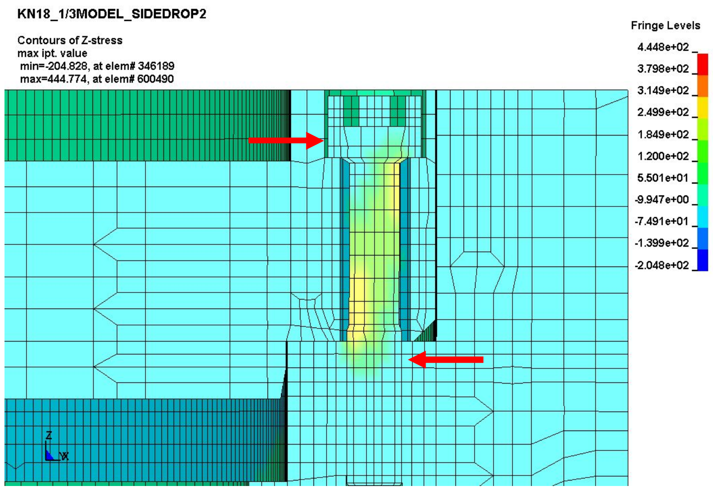
[Stress distribution of the cask body]

◆ IMPACT BEHAVIOR : 9m side drop

- (▿) Shear behavior on the lid bolts nearest to the target
- (▹) Deformation in the top and bottom impact limiter
- (▹) Actual test results : outer welds of impact limiter near the target tore apart, and some of the wood layers extruded during the impact



[Deformation in the impact limiter]

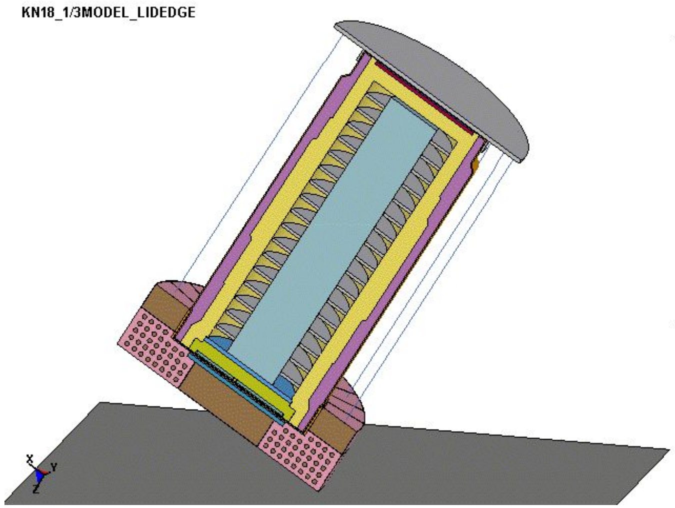


[Shear behavior on the lid bolts]

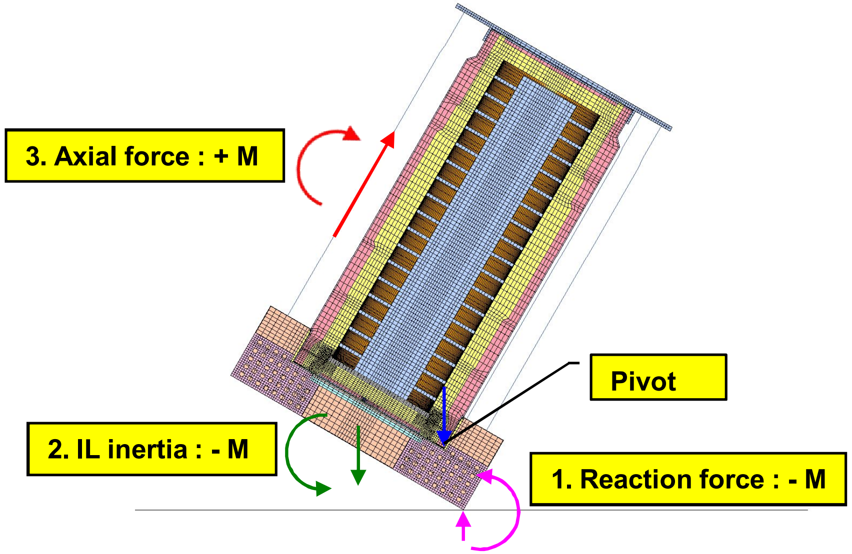
[Weld failure in the impact limiter]

◆ IMPACT BEHAVIOR : 9m lid edge drop

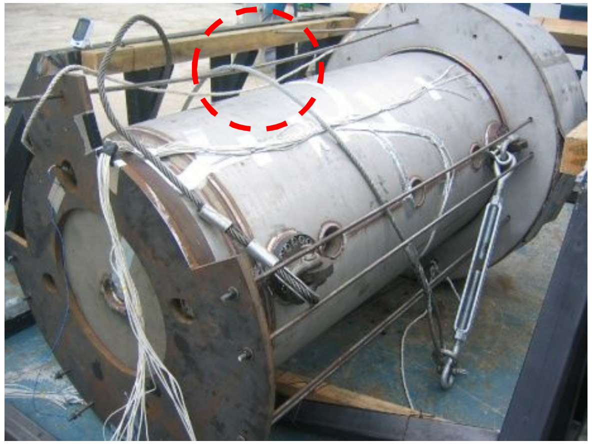
- (▿)Drop orientation : CG over the impact point
  - *the angle of 60° from the cask axis to the target*
- (▿)Loading on the impact limiter
  - lid edge of the cask -> pivot
  - reaction force -> counter-clock wise M
  - IL own inertia force -> counter-clock wise M
  - tie-rod axial force -> clock wise M
  - -> (▹) two of the 12 tie-rod failed
- (▹)Drop simulation results



[Drop animation]



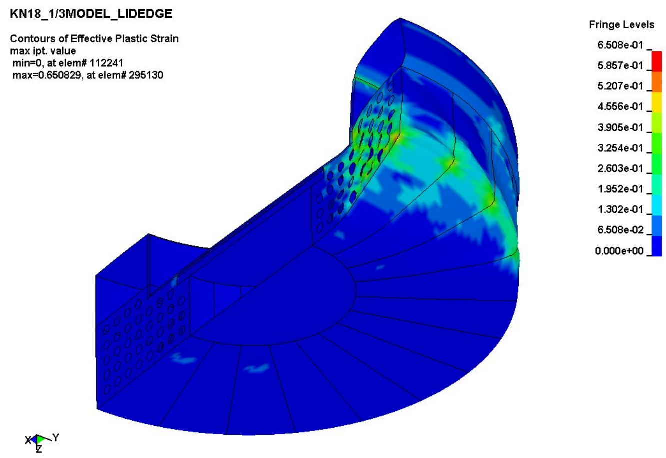
[Drop orientation]



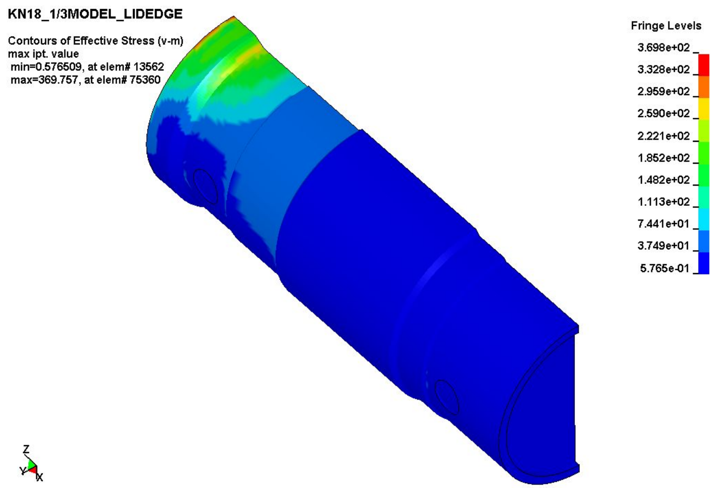
[Failure of the tie-rod]

◆ IMPACT BEHAVIOR : 9m lid edge drop

- (▿)Stress distribution of the cask body
- (▹)Plastic strains in the top impact limiter
- Fillet welds of the impact limiter were assumed not to be failed in the analysis
  - -> (▹)some welds failed during impact in the actual test
  - -> analytical assumption : conservative prediction of cask stress



[Plastic strains in the top impact limiter]



[Stress distribution of the cask body]

[Deformation in the impact limiter]

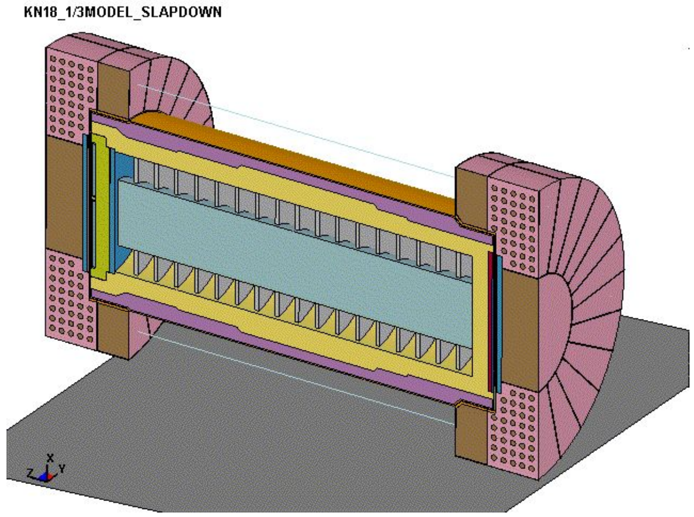
5. Numerical and Experimental Results

- IMPACT BEHAVIOR : 9m slap down drop
  - (▿)Drop orientation : CG over the impact point (X)

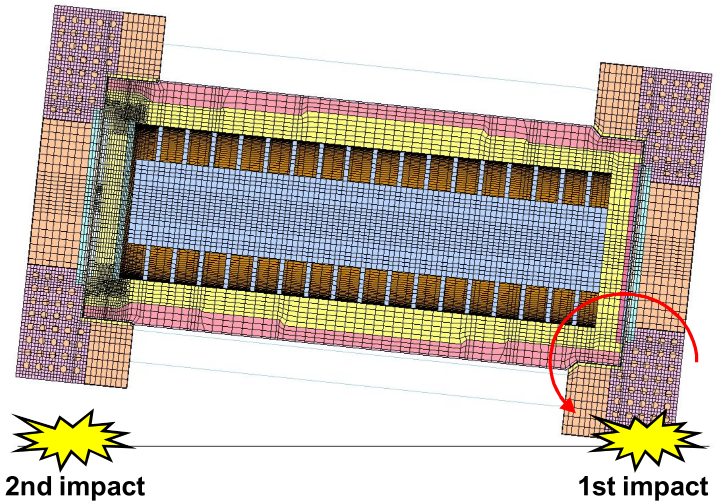
    - an angle of 6° from the cask axis to the target

    - after 1st impact, cask rotated under gravity

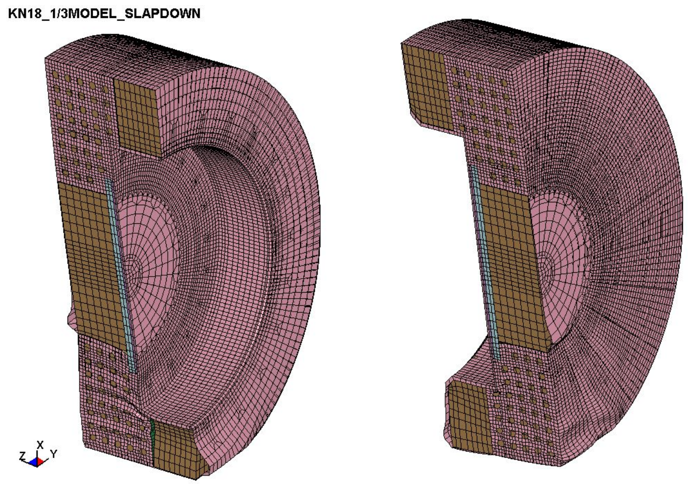
    -> 2 impact, 2nd impact > 1st impact : rebound
  - (▹)Drop simulation results
  - (▹)Deformation in the impact limiter



[Drop animation]



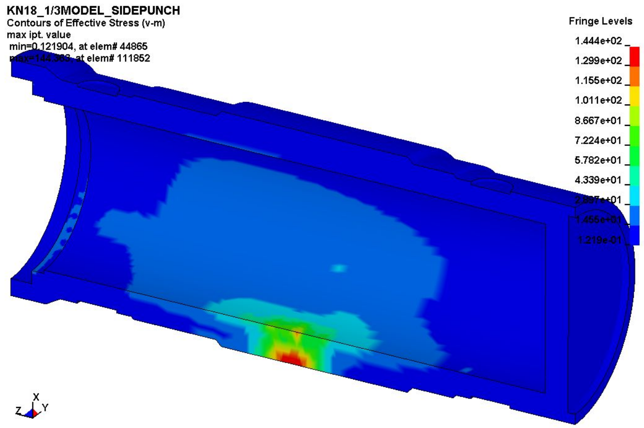
[Drop orientation]



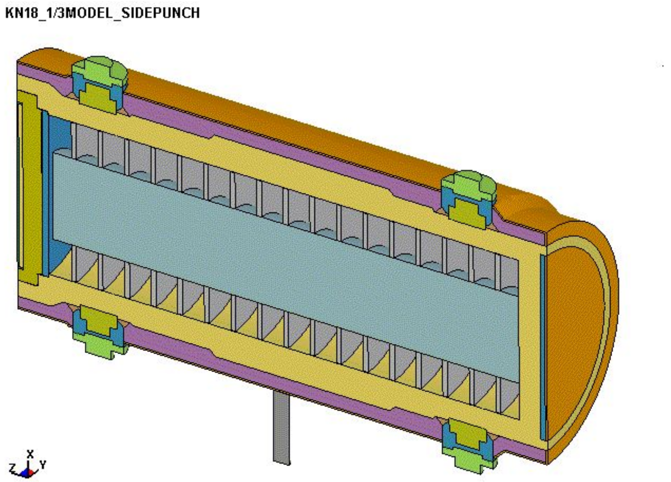
[Deformation in the impact limiter]

◆ IMPACT BEHAVIOR : 1m side puncture

- (▿)Drop orientation : CG over the puncture bar
  - *1m free drop onto the puncture bar*
- (▿) Drop simulation results
- Cask deflected like a beam with a single support
- (▹)Stress distribution of the cask body
  - *stress concentration near the impact point*
- (▹)Punctured shape at the resin layer
  - *indentation of about 50mm in the resin layer*



[Stress distribution of the cask body]



[Drop animation]

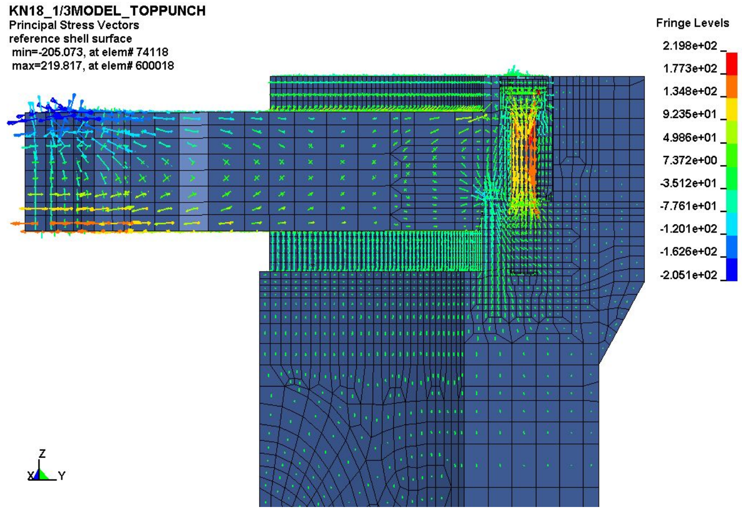
[Punctured shape at the resin layer]

◈ IMPACT BEHAVIOR : 1m top puncture

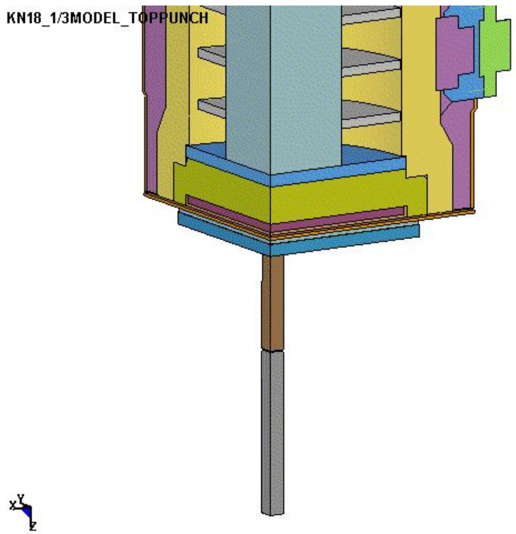
- (▿)Drop orientation : CG over the puncture bar
- (▿) Drop simulation results
- (▹)Compression load path at the lid part
- (▹)Punctured shape at the impact limiter

- indentation of about 150mm, bent pin

- the impact behavior was dominated by crushing of the wood



[Load path at the lid-body interface]



[Drop animation]

[Punctured shape at the impact limiter]

6. Validation of Numerical Method [Comparison of results]

◆ OUTLINE OF VALIDATION

- Numerical results were compared with test results to verify the numerical simulation method used in the analyses
- *Strain and acceleration measurements provide the essential components for the validation of the numerical methods*
- Comparison items
  - deformation behavior
  - acceleration trace
  - strain trace

◆ DEFORMATION BEHAVIOR

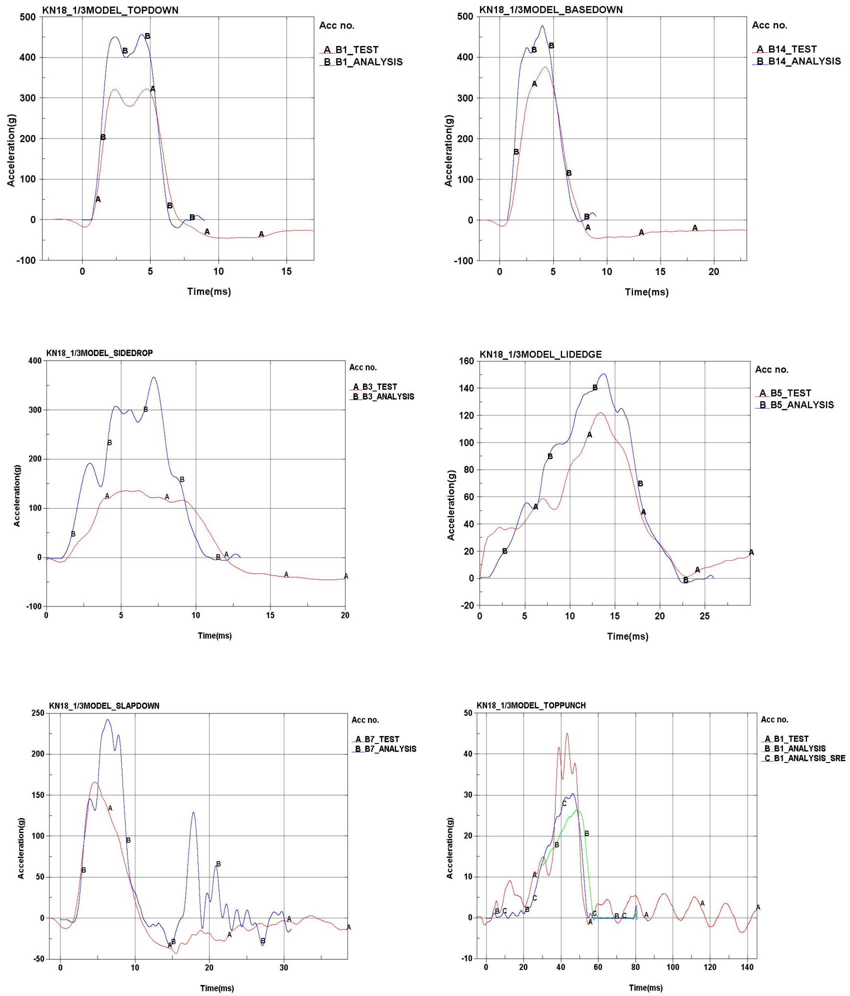
- (▹)In general, there was good agreement between the analytical and test results
- But, some fillet welds of the impact limiter housing failed in the actual test

  -> conservative results

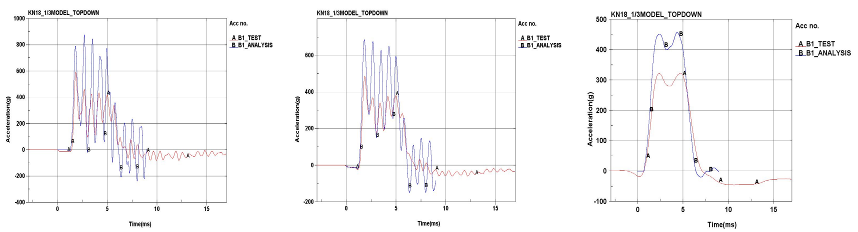
[Comparison of deformation behavior]

ACCELERATION TRACE

- Acceleration time histories were extracted from the FE model at the nodes nearest the accelerometers in the test
- Both data were filtered using same filtering method and same cut-off frequency
- (▿) Three different cut-off frequencies of 1650, 1000, 300Hz were applied
- (▹)Comparison of acceleration trace(300Hz)
- In general, acceleration traces from the analysis correspond very well with those from the test in terms of shape, magnitude, time scale
- Conservatively over-predict test results



[Comparison of acceleration trace(300Hz)]

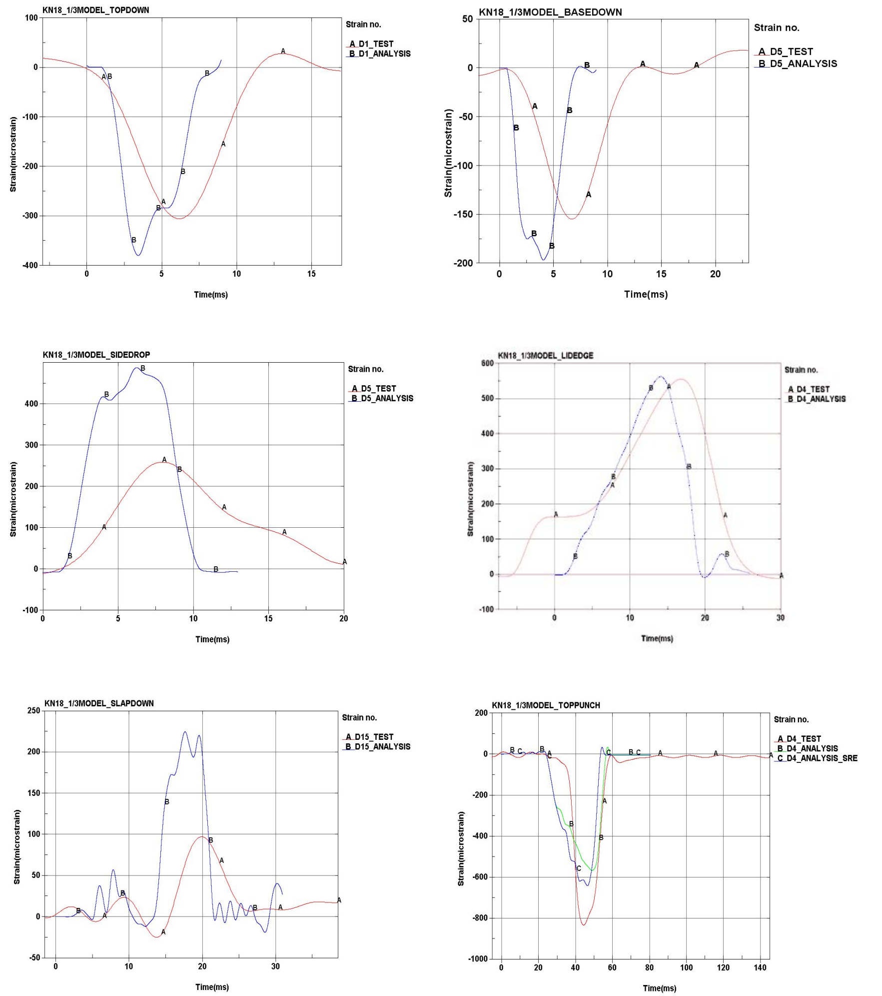


[1650Hz] [1000Hz] [300Hz]

[Filtering of measurement data]

STRAIN TRACE

- Strain time histories were calculated from the relative distance between the nodes nearest the strain gauges in the test
- As in the acceleration data, both data were filtered using same method
- *Three different cut-off frequencies of 1650, 1000, 300Hz was used*
- (▷)Comparison of strain trace(300Hz)
- In general, as in the acceleration data, strain traces from the analysis also correspond very well with those from the test
- Conservatively over-predict test results



[Comparison of strain trace(300Hz)]

7. Summary and Conclusion

- In this study, a series of actual drop tests were performed using a 1/3-scale model of newly developed KN-18 SNF transport cask in Korea.

- In addition, numerical simulations of the scale model cask were performed for all the drop test conditions using same numerical method used in the safety analyses of the real cask.

- Dynamic impact characteristics of the KN-18 SNF transport cask under free-drop conditions have been investigated from the test and numerical simulation results.

- The numerical method used in the analyses have been validated through a comparison of the test and numerical results.
  In general, the numerical results are in good agreement with the test results.
  In addition, the numerical results consistently and conservatively over-predicted the test results for most of the evaluated cases.

- These good correlations with the drop test results demonstrate that the numerical simulation method used in the analyses of KN-18 SNF transport cask is robust and reliable in simulating and predicting the dynamic impact behavior of the cask.