EVALUATION OF THE INFLUENCE OF TEMPERATURE BELOW 80˚C AND STRAIN RATE ON COMPRESSIVE PROPERTY OF WOOD FOR SHOCK ABSORBERS

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ABSTRACT
Generally, to evaluate impact analysis in the event of an accident, the mechanical properties of a shock absorbent material such as wood have been used at room temperature. However, there is potential for the impact acceleration to increase due to softening of the wood with the increase of temperature up to a locking-up point. In this study, three wood species (oak, fir-ply and balsa) were selected, and a series of static and impact material tests performed to investigate the temperature dependence and strain rate effect on the compressive properties. Consequently, the need to take these influences into consideration in cask design was confirmed due to the decline in impact energy absorption performance beyond 50˚C.

INTRODUCTION
Generally, to evaluate impact analysis in the event of an accident, the mechanical properties of a shock absorbent material such as wood have been used at room temperature in the Safety Analysis Report of transport casks. However, there is potential for the impact acceleration to increase due to softening of the wood with the increase of temperature and consequently reach a locking-up point due to the remarkable deformation of the shock absorbers [1], [2]. In this study, as typical materials used for shock absorbers of transport casks in Japan, three wood species (oak, fir-plywood and balsa) were selected, and material data related to compressive properties was acquired in static and impact tests at various temperatures (20, 50 and 80˚C) and deformation speeds (0.1, 10 and 1000mm/sec). According to these results, while the compressive strength reaches 70-80% of that at 20˚C with the increase of temperature, the dynamic strength increases up to 1.2 times the static strength with the increase of the strain rate over 0.1/sec. Moreover, to investigate the effect of the temperature and strain rate effects of the wood on the impact response of the full-scale cask, sensitivity horizontal drop analyses with LS-DYNA code were performed for the 9m horizontal drop test.

COMPRESSIVE CRUHSHING TEST METHOD

<u>Test condition</u>
Table 1 shows the compressive crushing test condition. The test parameters are wood species, grain direction, loading speed and temperature. Fig. 1 shows the dimension of the test specimen. To

obtain the compressive crushing characteristic of the wood under the constrained condition, the test specimen set comprised the compressive core wood, restraining ring wood and steel pipe. The size of the compressive wood specimen was 60mm in diameter and 80mm in height, considering the locking-up strength of the wood at strain exceeding 50% and the allowable loading force (Max. 500kN) of the test device. The test specimen was restrained by the same wood ring (130.8mm in outer diameter and 80mm in height) set in the steel pipe (139.8mm in diameter and 100mm in height).

Three wood species (oak, fir-plywood and balsa) were selected as typical materials for the shock absorber as used on transport casks in Japan. For each type of wood, clear-grained large blocks without knots and splits were selected. As wood may be considered an orthotropic material, test specimens were machined from this block bidirectionally, along the axes parallel to and perpendicular to the grain respectively as shown in Fig. 2. For the temperature condition, considering the IAEA requirements for the allowable surface temperature limit of the type B package (85˚C), three different temperatures (20, 50 and 80˚C) were considered. The moisture content value was controlled according to the measuring method defined in JISZ2102-1994 [3] as shown in Table 2. After complete drying, the test specimens were cured in the furnace at the designated temperature and relative humidity for 168 hours and the moisture content allowed to settle to less than 10% before being tested.

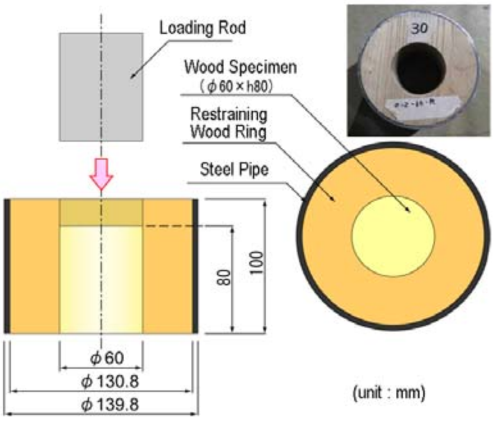


Fig. 1 Dimension of the Test Specimen

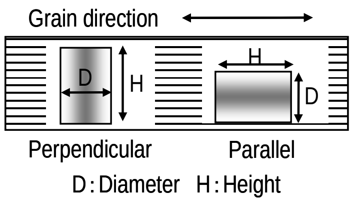


Fig. 2 Grain Direction of the Test Specimen

Table 1 Compressive crushing test condition

Wood Species	Oak, fir-plywood, balsa
Grain Direction	Parallel to the grain Perpendicular to the grain
Specimen size	f³ 60mm ~ H80mm
Moisture content	below 10%
Loading Speed	0.1mm/sec (Static) 10 mm/sec (Dynamic) 1000mm/sec (Impact)
Test temperature	20˚C, 50˚C, 80˚C
Test number	54 conditions ~ 3 samples

Table 2 Wood species and characteristics

Species	Density [g/cm^3]	Moisture Content [%]		
		20˚C	50˚C	80˚C
Oak	0.82 }0.05	5.7-6.3	5.7-5.9	4.7-4.9
Fir-plywood	0.56 }0.04	5.0-7.0	5.8-6.1	4.7-4.8
Balsa	0.14 }0.02	5.5-7.1	5.2-5.7	4.6-6.9

Test Method

Fig. 3 shows the specification of the loading device and the equipment of the test device. To deform the test specimen in the appropriate direction, the steel forcing punch was set in the guide tube with the bearing system and the forced displacement measured by two laser displacement sensors attached to the guide tube. The sampling rates for the static/dynamic and impact test were set to

100Hz and 50kHz respectively. To maintain the designated temperature of the test specimen during the test, a thermally insulated rubber heater was set around the test equipment and controlled by a thermocouple incorporated within the wood ring. To investigate the strain rate effect of the material, three loading speeds were considered as shown in Table 1.

In the previous 9m drop test with the full-scale cask [4], as the shock absorber was subject to a 30% deformation ratio over a period of around 20msec, the average strain rate was estimated at 15/sec. Since the deformation speed for the 80mm height specimen would be 1200mm/s, the loading speeds for the static, dynamic and impact test were set to 0.1, 10 and 1000 mm/sec respectively.

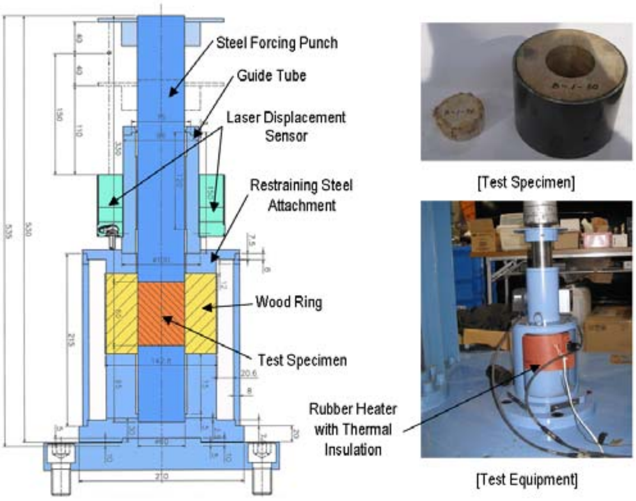


Fig. 3 Specification of the Test Equipment

COMPRESSIVE CRUHSHING TEST RESULTS

The behavior of the wood material with respect to the grain direction (parallel and perpendicular to the grain) was evaluated for static, dynamic and impact test conditions. Fig. 4 shows the test specimen after the compressive test, while Figs. 5 and 6 show the nominal stress-strain relationships and the energy absorption values per unit mass for static and impact testing.

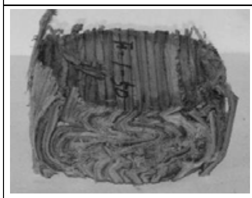
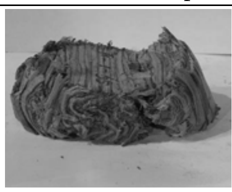
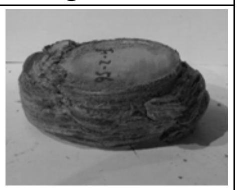
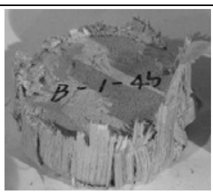
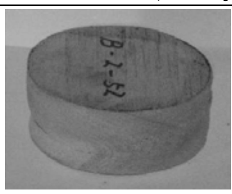
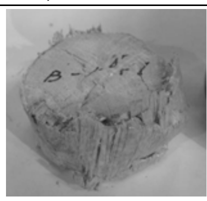
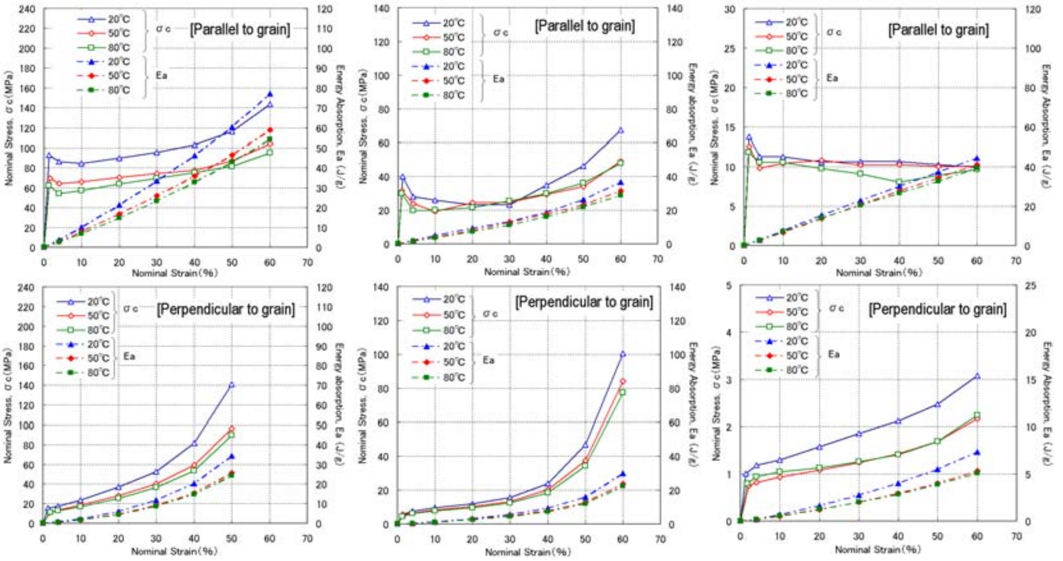
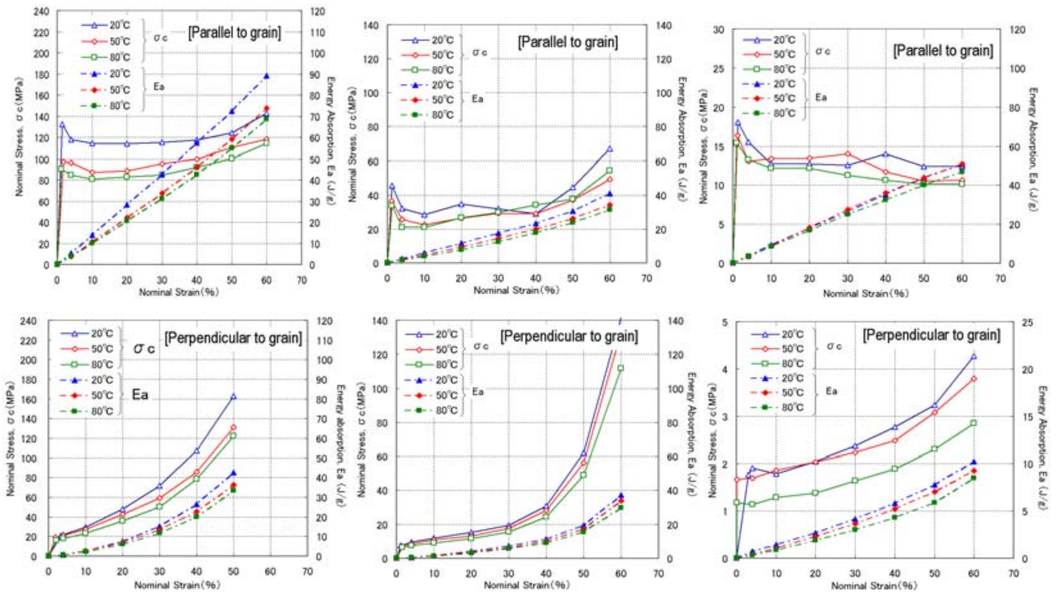
Static Testing		Impact Testing	
 Parallel	 Perpendicular	 Parallel	 Perpendicular
(Fir-Plywood)			
 Parallel	 Perpendicular	 Parallel	 Perpendicular
(Balsa)			

Fig. 4 Test Specimen after the Compressive Crushing Test



(Oak) (Fir-Plywood) (Balsa)

Fig. 5 Nominal Stress-Strain Relationships and Energy Absorption Values in Static Testing



(Oak) (Fir-Plywood) (Balsa)

Fig. 6 Nominal Stress-Strain Relationships and Energy Absorption Values in Impact Testing

Static Testing Results

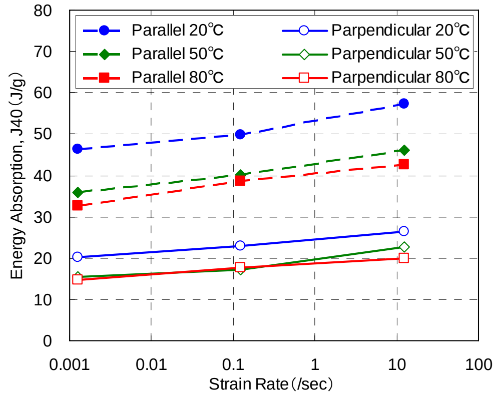
Under static loading with the constrained test specimen, the perpendicular loading orientation is typically 2 to 4 times as stiff as the parallel loading orientation at 40% strain as shown in Fig. 5. While the specimens tested with load perpendicular to the grain crushed uniformly in the region below 50% strain, a rapid increase was observed in the gradient of the stress strain curve due to locking-up caused by the lack of porosity of the specimen. On the other hand, as the specimens tested with load parallel to the grain buckled early in the loading process, the stress-stain curve revealed a significant peak at the start of the deformation. The onset of locking-up was delayed for parallel loaded specimens by the buckling process. As locking-up commenced, the stress-strain curve steepened rapidly except in the case of balsa wood, as also occurred in the perpendicular load case.

Impact Testing Results

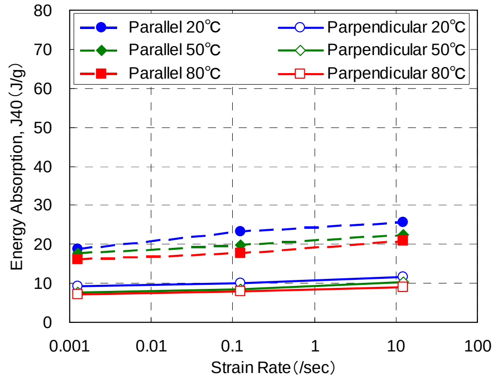
Under impact loading with the constrained test specimen, the perpendicular loading orientation was also typically 2 to 4 times as stiff as the parallel loading orientation at 40% strain as shown in Fig. 6. The crushing stress-strain behavior was very similar to the results achieved for specimens under static loading. The effect of the strain rate was also found to be significant. Fig. 7 shows the strain rate and temperature effect on the energy absorption value up to 40% strain, J_{40}. In both perpendicular and parallel loading cases, the J_{40} values exceeded those for the corresponding static strain-rate results by a factor of about 1.2, even if at high temperature.

Temperature Influence

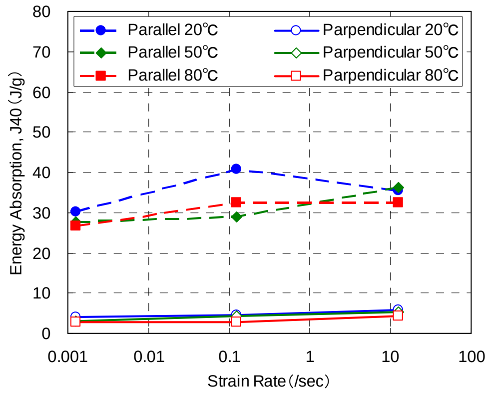
The effect of temperature was also found to be significant as shown in Fig. 7. In both perpendicular and parallel loading cases, J_{40} values for 80˚C specimens were less stiff than the ambient specimens (typically by a factor of 0.7 to 0.8) as described in the Wood Handbook [1].



(Oak)



(Fir-Plywood)



(Balsa)

Fig. 7 Strain Rate and Temperature Effect on the Energy Absorption value, J40

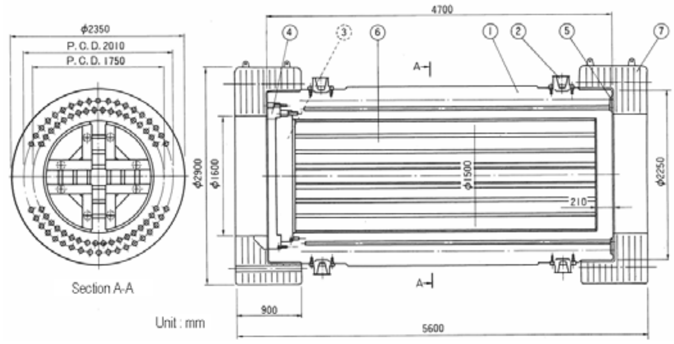
INFLUENCE ON THE IMPACT DESIGN OF THE CASK

To investigate the effect of the temperature and strain rate effects of the shock absorbent material on the impact response of the cask, sensitivity horizontal drop analyses with LS-DYNA code were performed for the 9m horizontal drop test using the full-scale ductile cast iron (DCI) cask under -40˚C as shown in Fig. 8 [4].

Fig. 8 9m Horizontal Drop Test [4]

Drop Test Description

Fig. 9 shows the dimension of the cask, which had a double lid structure and weighed 105MN. The materials used for the cask body and shock absorber were DCI and Fir-Plywood respectively. Figs. 10 and 11 show examples of the drop test results.



No.	Item	Material
①	Cask Body	Ductile Cast Iron
②	Trunnion	SUSF6NM
③	Primary Lid	SUSF6NM
④	Secondary Lid	SUSF6NM
⑤	Bottom Plate	SUSF304
⑥	Dummy Weight	SS41
⑦	Impact Limiter	Fir-Plywood

Fig. 9 Dimensions of the full-scale ductile cast iron cask

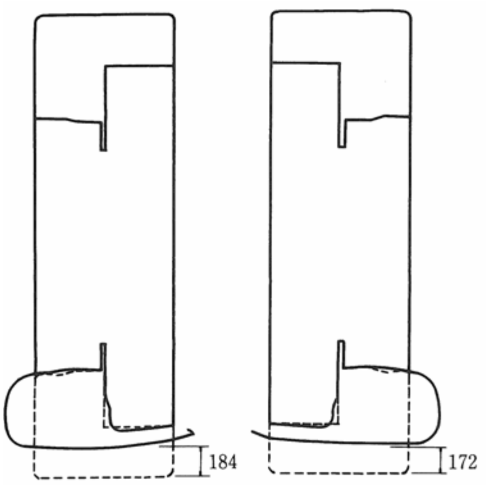


Fig. 10 Shock Absorber Deformation after the Drop Test

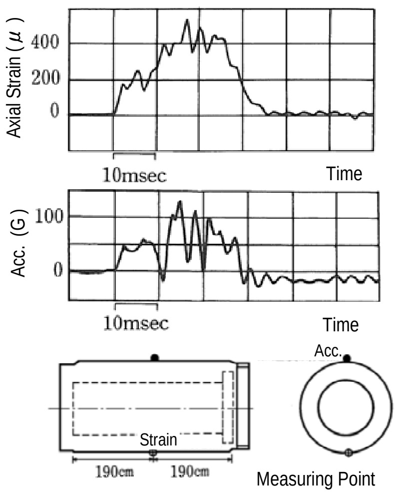


Fig. 11 Measured Time Histories

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Sensitivity Analysis Case

Table 3 shows the condition of the sensitivity analysis. Case 1 was considered to validate the analysis model by comparing the test results. The temperatures considered were -40 (drop test condition), 20 and 80˚C. Fig. 12 shows an analytical model of the horizontal drop test. This model is formed as a 1/2 symmetric model considering the cask structure. An initial velocity of 13.3m/s, equivalent to the free drop velocity from a height of 9m, and gravity acceleration of 9.8m/s^2, were set to the cask model. Shock absorbent wood material (Fir-Plywood) was simulated as isotropic crushable foam (material type 63 [5]) with the multi-linear stress-strain curve as shown in Fig. 13. As these material properties were determined from the material test results under constrained conditions, Poisson's ratio was set to zero.

Validation of the Analysis Model

Fig. 14 shows the time histories obtained in the drop analysis, from which the high frequency components were removed using a low pass filter (1 kHz). The consistency of the calculated shock absorber crush data is confirmed by the deformation data as shown in Fig. 10. The amount of deformation obtained from the drop analysis in Case 1 (175mm) was almost equivalent to that measured in the drop test, with crushing to 172 and 184mm on the lid and bottom ends respectively. Further confirmation can be obtained from Fig. 14, which reveals a peak impact force of 1.07MN for Case 1. For a total weight of 105MN, the maximum acceleration would be about 100G. This value is very close to the acceleration observed in Fig. 11.

Sensitivity Analysis Results

While the deformation amount for Case 2 using the static material data at ambient temperature was 214mm, that for Case 3 using the impact material data at 80˚C was 216mm. Little difference in crush behavior emerges between Cases 2 and 3 because of the decrease of energy absorption ability due to high temperature potentially being cancelled by the strain rate effect. Likewise,

Table 3 Sensitivity Analysis Condition

Case #	Case 1	Case 2	Case 3
Cask	DCI Cask		
Drop condition	9m horizontal drop onto unyielding target		
Shock absorber material	Fir-Plywood (Parallel to grain)		
Shock absorber temperature	-40˚C	20˚C	80˚C
Wood data	Static [4]	Static Fig. 5	Impact Fig. 6

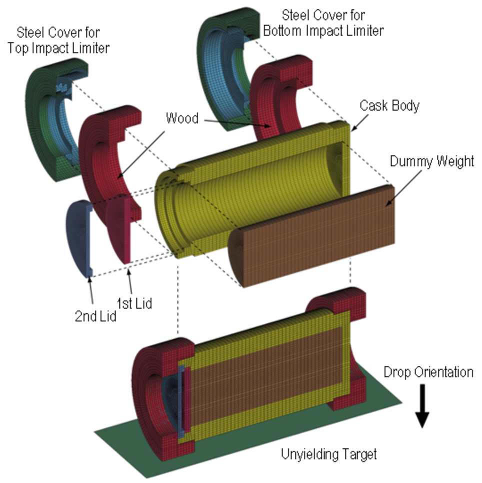

Fig. 12 Analytical model

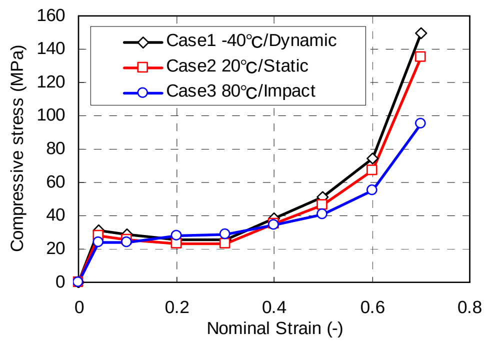

Fig. 13 Stress-Strain Curve for Fir-Plywood Wood Material

while the peak impact force for Case 2 using static data at room temperature was 103MN, that for Case 3 was 96MN (a decrease of only 7%). Consequently, it could be concluded that no remarkable difference emerged in the stress values between Cases 2 and 3.

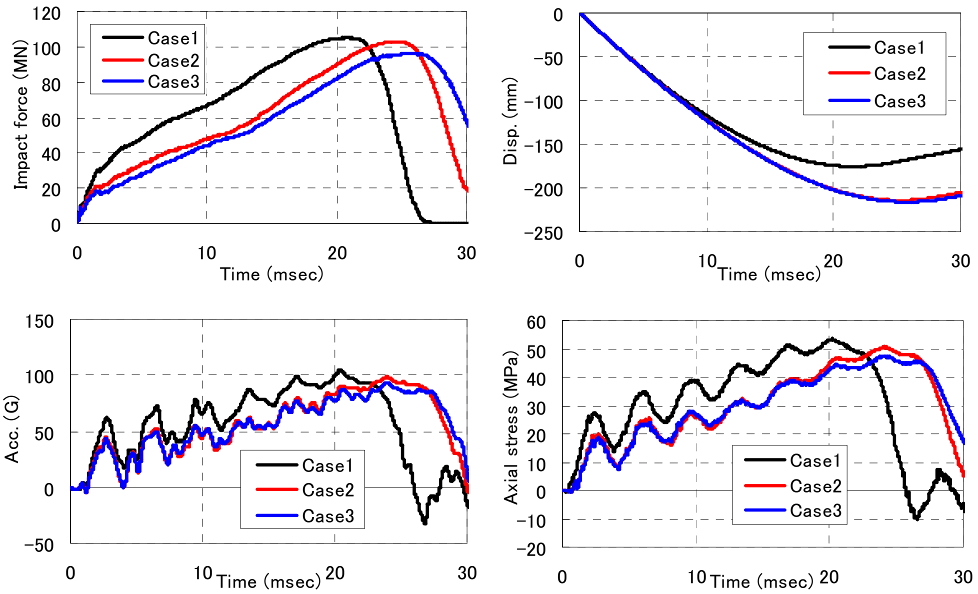

Fig. 14 Various Time Histories obtained in the Drop Analyses

CONCLUSIONS

As a typical material used for shock absorbers of transport casks in Japan, three wood species (oak, fir-plywood and balsa) were selected, and data concerning temperature (20, 50 and 80˚C) and strain rate (0.001, 0.1, 10/sec) dependence on compressive properties were acquired in static and impact tests. According to these test results, while the compressive strength reached 70-80% of that at 20˚C with the increase of the temperature, the impact strength increased up to 1.2 times the static strength with the increase of strain rate over 0.1/sec. Consequently, it could be concluded that if the wood model considering the strain rate effect at the high temperature were applied to the impact design of the cask, its impact behavior during the impact loading would not be significantly affected comparing the impact response using the wood model at room temperature, in which temperature dependence and strain rate effect were not considered.

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