Technical Papers

Introduction of Simulation of Falling Object Protective Structures

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With the aim of securing the safety of construction machine operators, various safety standards have been established by ISO, etc. This paper describes PAM-CRASH which is a computer program for simulating the fall of an object onto the cab roof of a construction machine from above.

Key words: *FOPS, CAE, PAM-CRASH, Collision Analysis, Safety Standards.*

1. Introduction

Normally, the operator of a construction machine sits on a seat in a closed space (cab) during machine operation. When the operator of a hydraulic excavator or some other machine is excavating an elevated place above the cab by extending the work equipment, masses of soil, rock, etc. may fall onto the cab. Therefore, construction machines are equipped with falling object protective structures (FOPS) for protecting their operators. FOPS are required to meet certain strength standards according to their uses. This paper introduces PAM-CRASH which is a computer program for simulating the performance of FOPS to determine whether or not FOPS meet the prescribed standards.

2. Safety standards for FOPS

Safety standards for FOPS are prescribed in ISO 3449-1992 and SAE J231. In short, they provide that when a weight of prescribed shape and prescribed mass (falling object) is let free-fall onto the cab ceiling of a construction machine from a prescribed height (see **Fig. 1**), the deformation of the part of the ceiling onto which the weight fell shall not reach the deflection limiting volume (DLV: see **Fig. 2**).

In the prescribed FOPS performance tests of Komatsu hydraulic excavators and bulldozers, it has been confirmed that the deformations caused by falling objects do not reach the DLV.

Fig. 2 schematically shows the DLV. The DLV is a volume which roughly and a little bit largely simulates the condition of a machine operator sitting on the seat. It serves as the criterion of the provision that the deformation caused by a falling object shall not reach the DLV. ISO 3164 specifies dimensions of the DLV.

Fig. 1 FOPS performance test

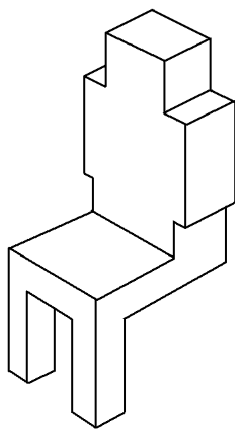


Fig. 2 DLV (deflection limiting volume)

3. Falling object protective structures (FOPS)

Various types of FOPS are used according to machine specifications (and applicable safety standards). They include, for example, a sheet metal structure fitted as an option to the cab (see **Fig. 3**) and a structure which covers only the top light of the cab (see **Fig. 4**).

These FOPS have slits in their structural member to permit the operator in the cab to look up through the top light.

As already mentioned, stringent safety standards have been established by ISO, etc. As a result, more and more cabs are equipped with FOPS as options. Under this condition, so-called FOPS cabs which are provided with FOPS functions as standard have been developed.

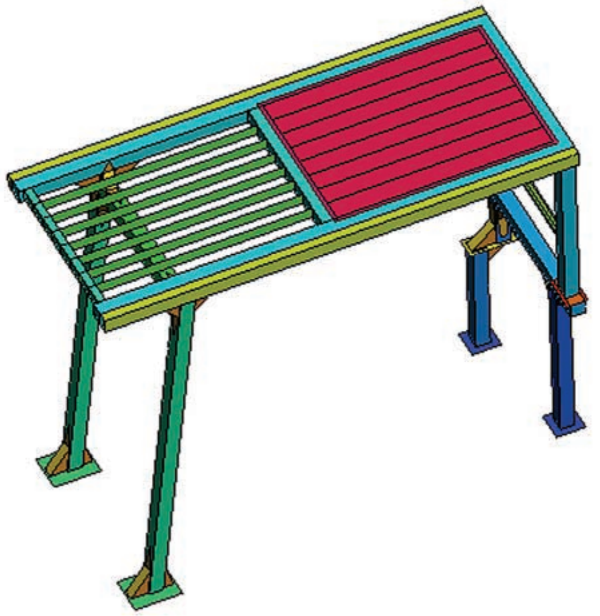


Fig. 3 FOPS (structure covering entire cab ceiling)

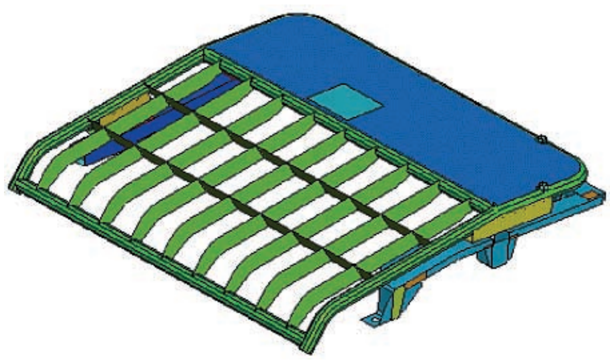


Fig. 4 FOPS (structure covering only top light of cab)

4. Problems involved in development

Needless to say, FOPS are designed based on the amount of deflection caused by a falling object. In manual calculations, however, there was no alternative but to compute the amount of deformation on the basis of static load assuming a perfect elastic body. The calculated values seldom agreed with the measured values. So far, FOPS have been designed based on empirical knowledge. Therefore, until actual FOPS are tested, the level of their strength can hardly be known. In worst cases, actual FOPS have to be tested repeatedly. This is ineffective in terms of cost and labor. Actually, it is not that we have repeated trial and error so many times. The fact is that we could not have confidence in the quality of design on the drawing board.

Under those conditions, we considered the possibility of using CAE to simulate the falling of an object onto FOPS. Eventually, we decided to use PAM-CRASH which is capable of simulating the time-serial change of the load applied to the FOPS members after a falling object makes contact with them, up until the occurrence of elastic-plastic deformation and fracture of the FOPS.

5. Introduction of PAM-CRASH

Here, we shall briefly explain the functions of PAM-CRASH focusing on those functions which have to do with the simulation (calculations) of FOPS. Needless to say, the functions of PAM-CRASH are not limited to the ones described below.

5.1 Ability to define mechanical properties in detail

PAM-CRASH directly defines the stress-strain curve of a material. With measured values, the stress-strain curve becomes complicated. By contrast, PAM-CRASH is capable of expressing the curve by a maximum of eight straight lines (one in the elastic region and seven in the plastic region). By defining a maximum plastic strain, it is possible even to simulate the occurrence of a rupture.

5.2 Easy definition of contact

With other computer programs which are capable of solving contact problems, it is normally necessary to previously decide a point of contact (and make suitable arrangements to cause the contact). With PAM-CRASH, it is necessary only to list up the members which are likely to make contact with each other. For example, if you consider that this member (having specific material characteristics) will make contact with that member (having specific material characteristics), all you have to do is define the combinations of members which are likely to make contact with each other by separate groups of material characteristics. This saves time and labor significantly.

5.3 Time-serial calculation

In the FOPS calculations, the analyzer simulates the phenomenon that lasts for approximately 0.05 second, with the falling object about 1 mm above the cab ceiling member as the initial state, from the time right before the collision till the deflection of the ceiling member stops after the bouncing of the object. PAM-CRASH divides the analyzer-set simulation time into minute time steps and performs time-serial calculations. It should be noted, however, that PAM-CRASH can perform only time-serial calculations: it cannot directly calculate a steady state as in static analysis.

6. Calculation examples

6.1 Example of calculation models (FOPS cab)

Fig. 5 shows a 3D-CAD model of the cab of a large bulldozer. A calculation model is prepared from this 3D-CAD model. Only the part above the cross section shown in Fig. 5 shall be modeled. (It has been confirmed that in FOPS calculations, the presence or absence of the part below the cross section makes very little difference since the collision is extremely instantaneous and local.) The window glass and other members which have no direct bearing on the FOPS strength shall also be left out of consideration.

Fig. 6 shows the FOPS cab calculation model prepared. The interior (inside) of this model is as shown in **Fig. 7**. Since holes for fitting the speaker and rear windshield wiper motor have been drilled in the cab structural member, the FOPS strength has declined and hence, a large deflection can occur during collision. Therefore, these factors are also reflected in the model.

Fig. 8 shows the falling object calculation model. As shown, the falling object shall be directly modeled. The shape and mass of falling object are specified in ISO 3449-1992.

In the initial state for calculations, the falling object is set in position right before it makes contact with the FOPS as shown in **Fig. 9**. When the falling object is let free-fall from the height specified in ISO as shown in Fig. 1, it does not make contact with the FOPS till it hits against the FOPS. On the calculation model, therefore, the falling speed right before the collision is given to the object to make it hit against the FOPS.

Next, the mechanical properties of the FOPS structural members are defined. From the mill sheet, etc. of the steelmaker, a stress-strain curve as shown in **Fig. 10** shall be decided.

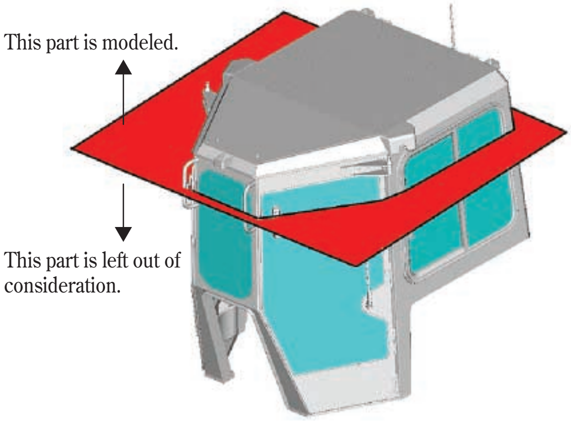


Fig. 5 3D-CAD model of FOPS cab

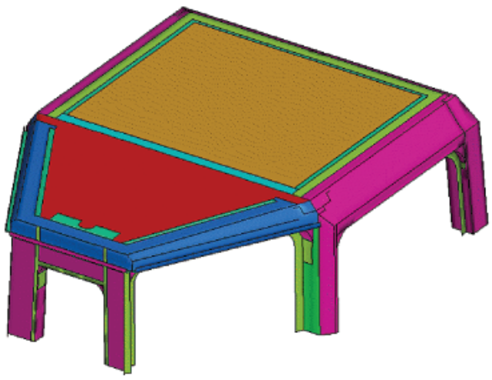


Fig. 6 FOPS cab calculation model

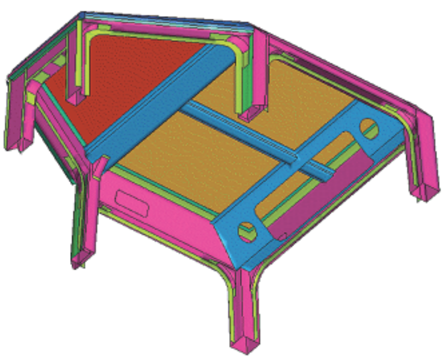


Fig. 7 Inside of FOPS cab calculation model

Fig. 8 Falling object calculation model

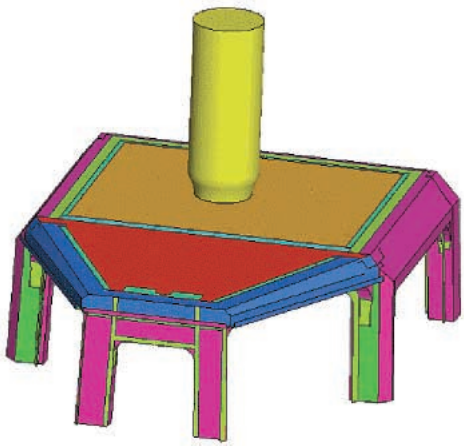


Fig. 9 Calculation model (initial state)

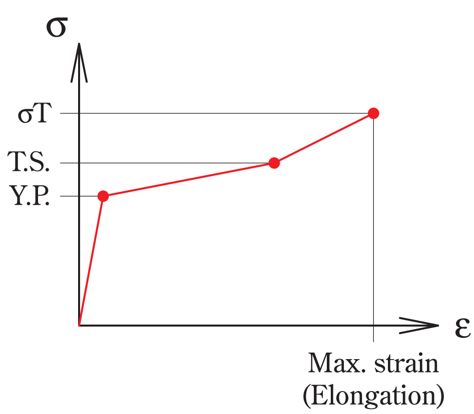


Fig. 10 Stress-strain curve for calculation model

Here, a stress-strain curve which expresses the stress-strain relationship up to the occurrence of a rupture by three straight lines is used for the calculations. The model is subject to elastic deformation up to the yield point (Y.P.), from which to the yield tensile strength (T.S.) the model is subject to plastic deformation. The plastic deformation of the model continues till the model ruptures under the true rupture stress, σ_T. The validity of these mechanical properties is to be judged by checking them against the measured values obtained by FOPS test. (For an example of verification, see Section 7.)

6.2 Examples of calculation results (FOPS cab)

Calculations with the model prepared in 6.1 give the collision-induced deformation (and animation) as shown in **Fig. 11** and **Fig. 12**. From these, the time-serial deflection of the point that was subject to maximum deflection can be seen (**Fig. 13**).

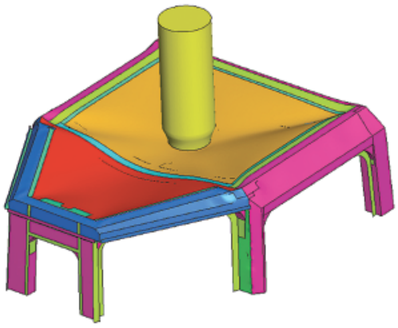


Fig. 11 Deformation (at time of maximum deflection)

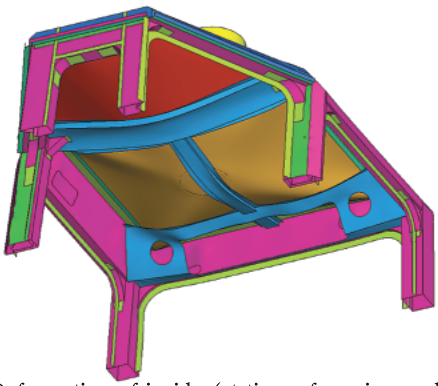


Fig. 12 Deformation of inside (at time of maximum deflection)

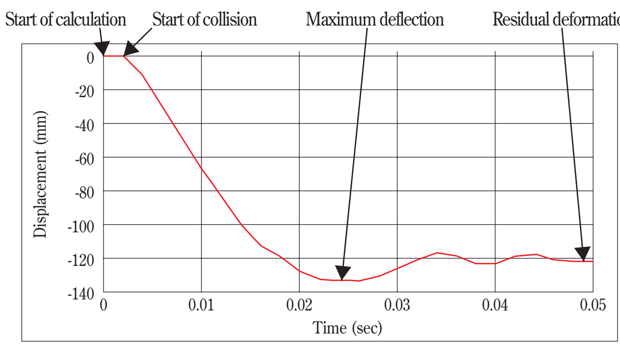


Fig. 13 Time-serial deflection (at maximum deflection point)

Fig. 13 plots the calculation results with time (sec) on the horizontal axis and deflection (mm) in falling direction on the vertical axis. It can be seen that the deformation reaches a maximum of 133 mm approximately 0.025 second after the collision. Therefore, the FOPS should be so designed that the calculated maximum deflection is smaller than the initial clearance between the DLV and the most affected point of the ceiling. It is extremely useful to know the maximum deflection of FOPS by the calculations described above.

7. Collation with measured values

In order to grasp the reliability of model calculations, the calculated values are checked against the measured values. Here, the calculation results obtained with three types of FOPS shall be checked.

	FOPS type	Maximum deflection (mm)		Residual deflection (mm)	
		Measured value	Calculated value	Measured value	Calculated value
PC400-6 *1	Guard with supports	— *4	65	18	20
PC228US-3 *2	Guard with supports	— *4	37	26	26.5
D475A-5 *3	FOPS cab	130	133	105	121

(*1) PC400-6

Both the calculated values and measured values meet ISO 3449-1992 Level II (when a cylinder weighing 229 kg is let free-fall onto FOPS from a height of 5.2 m, the FOPS deformation shall not reach the DLV).

(*2) PC228US-3

Both the calculated values and measured values meet the provision of Article 153 of the Industrial Safety and Health Law for head guards with supports (when a steel ball 38.2 kg in weight and 30 cm or less in diameter is let free-fall onto the head guard, the head guard shall be free from rupture and residual deflection of 50 mm or more).

(*3) D475A-5

As with PC400-6, both the calculated values and measured values meet ISO Level II. In the test with actual FOPS, deflection sensors of non-contact type were attached to the DLV to measure time-serial deflection as in the model calculations. The measurement results are also shown in **Fig. 14**.

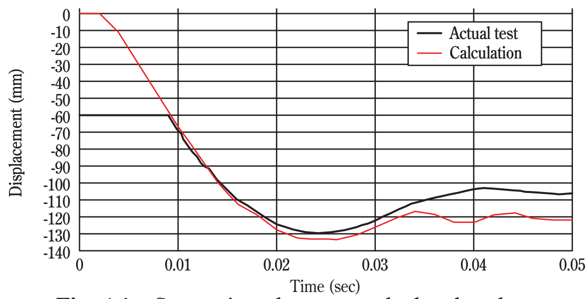


Fig. 14 Comparison between calculated and measured values (D475A-5)

(*4) The tests were focused on the FOPS meet requirement or not, measurement data is unavailable.

The reason why the measured values remained the same for the time from 0 to approximately 0.01 second is that the deformed cab ceiling was outside the measuring range of the sensors (measurement could be done only when the ceiling fell into the measuring range). The graph shows that the calculated values agree well with the measured values in terms of time and amount of maximum displacement.

8. Other calculation examples

8.1 Reproduction of FOPS which failed in test

Reproduction of a large deformation of the rear part of the ceiling of a FOPS cab of a bulldozer, around the hole for installing a rear windshield wiper motor (see **Fig. 15**).

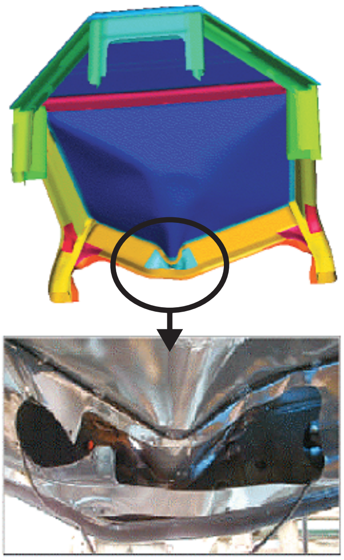
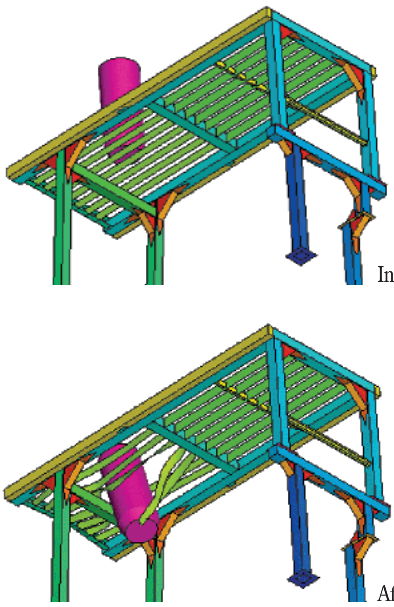


Fig. 15 Reproduction of FOPS which failed in test

8.2 Example of fracture

Results of calculations in which ISO Level II (free fall of 228 kg weight from height of 5.2 m) was applied to a guard which met ISO Level I (when a steel ball weighing 46 kg is let free-fall from a height of 3 m, the FOPS shall not reach the DLV) (see **Fig. 16**).



(Angle at which operator sitting on seat looks up cab ceiling)
The weight broke a strip of sheet, pushed away the adjoining strips, and fell through the guard.

Fig. 16 Example of fracture

9. Future plans

We could confirm that PAM-CRASH is sufficiently applicable to FOPS. In the future, we intend to continue making analysis with PAM-CRASH and improve the accuracy and reliability of analysis by carefully checking calculated values with measured values. In addition, we have plans to apply PAM-CRASH to simulate tipping over of construction machines.

Introduction of the writers

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[A few words from the writers]

It was rather difficult to perform the model calculations and collate the calculated values with the measured values. We are grateful to the staff of the Testing Department for their cooperation in measuring the time and amount of maximum displacement of the cab ceiling. Since the present simulation takes a lead time of one to two weeks, it is virtually impossible to calculate many different schemes as is possible in FEM analysis. In the future, therefore, in order to improve the probability of passing FOPS tests, we would like to prepare design indexes which permit making a fairly accurate judgment in the planning stage before the simulation.

[Note]