

Technical Paper

Introducing a Simulation of a Cab Protecting Operator during Rolling over of a Hydraulic Excavator

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Safety regulations are now also being enforced on hydraulic excavator; regulating cabs that have functions to protect operator during rolling over, as is currently required for other construction machinery. During development of these cabs, new tests are conducted in addition to the quality verification tests previously required. This report describes a technique to simulate these new quality verification tests using a computer.

Key Words: ROPS, EOPS, CAE, Safety Standards, PAM-CRASH

1. Introduction

1.1 Background

Unlike automobiles and other vehicles, hydraulic excavators can move only at a low speed, and not much attention has been paid to the safety of the operator during a crash while traveling. However, according to accident records of hydraulic excavators, several cases have instead occurred due to “rolling over of the excavator” or to “falling from a work area such as a cliff” (Fig. 1).

ISO (the International Standards Organization) is currently studying “safety regulations on cabs that have a protective structure during rolling over of hydraulic excavators.” In March 2003, JCMAS (Japan Construction Mechanization Association) already established safety standards, and Komatsu has been developing its products meeting these regulations. This paper describes a technique to simulate cabs of this protective structure for the operator during rolling over using a computer (hereinafter “analysis”).



Fig. 1 Hydraulic excavator during rolling over

1.2 Necessity of Analysis during Development

Prior to the development of a cabs with a protective structure for the operator during rolling over, the need for computer analysis has increased further, to resolve the following problems.

- 1) Needs for short development period and for low development cost (fewer retests)

A reduction in the number of retests is unavoidable in achieving a short development period. However, a cab that is once used in a quality verification test cannot be used (it is irreparable) because of the nature of strength verification tests. For this reason, a significantly long time is lost if a cab fails in a test (Fig. 2).



Fig. 2 Cab after quality verification test

2) Problem with delivery due date of testable cab

A cab is fabricated for retesting by providing reinforcement measures once a cab fails in a quality verification test. A long time is needed before a cab is delivered after drawings for improvement are handed over to the cab manufacturer.

3) Problem with accuracy of manual calculations

The deformation amount of a location of crash is calculated when the cab is crashed with pushing jig, work equipment, work equipment, and other elements. The only calculation method that can be used in manual calculations is to calculate the amount of deformation under an impact load based on a static load by a perfect elastic body. The calculation results hardly match the measured values, and designs have been made based on an empirical basis. The strength level, therefore, cannot be determined until a quality verification test of an actual machine is conducted. In the worst case, tests are conducted repetitively with machines, resulting in cost and time losses.

For these three reasons, computer analyses were conducted taking plastic deformation, buckling deformation, and contact into consideration.

2. Quality Requirements of Cab of the Operator Protective Structure during Tipping

As of December 2006, no safety standard or method to determine the strength of hydraulic excavators had been established by ISO. A strength evaluation method under the Japan Construction Mechanization Association (JCMAS) Standard (H018: 2003) is therefore described in the following.

2.1 Lateral Push Condition (Fig. 3)

A jig is pressed onto the pillar in the upper left of the cab and a load is applied toward the right side of the machine body from its left side. The load causes plastic deformation of the cab and absorbs energy. Pushing by the pushing jig is stopped when the target lateral load energy, E_s (see Note 1), is achieved and the load is removed. A cab is not accepted if part of it, which is deformed until lateral load energy is achieved, enters into a deflection-limiting volume (DLV), a human survival space.

Note 1: Lateral load energy E_s (in J)
 $E_s = 13000 \times (M/10000)^{1.25}$ [J]
 where M: Operating mass of test machine (in kg)

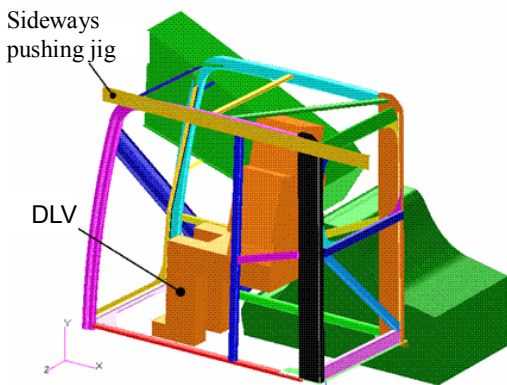


Fig. 3 Lateral push condition

2.2 Vertical Push Condition (Fig. 4)

The shape under a lateral push condition is continuously used after a sideways push test in 2.1. (The machine body is plastic deformed). A large jig covering the entire cab is pressed onto the machine body downward as a load. Pushing by the pushing jig is stopped when the target vertical load, L_v (see Note 2), is accomplished and the load is then removed. A cab is not accepted if part of it, which is deformed until the criteria load is gained, enters into a DLV.

Note 2: Vertical load L_v (in N)
 $L_v = 9.8M$ [N]
 where M: Operating mass of test machine (in kg)

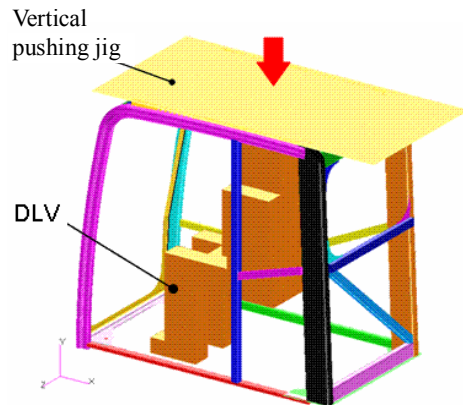


Fig.4 Vertical push condition

JCMAS defines cabs meeting the conditions described in 2.1 and 2.2 as cabs for hydraulic excavators with protective structure during rolling over.

2.3 Load and Energy

As mentioned above, two criteria are included in the quality requirements, namely, "load" and "energy," which are briefly described as follows.

Load: Maximum value of force pushed back by the cab when a force is applied to the cab by a pushing jig.

Energy: Energy is obtained by integrating a "load" by "displacement of a pushing jig" (See Fig. 5).

Both items are affected by the shape and progress of plastic deformation. For this reason, it is mandatory to ultimately fabricate an actual machine for testing and to verify its quality.

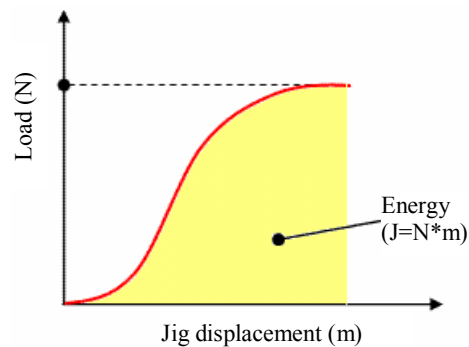


Fig. 5 Load and energy

3. Selection of Analytic Software

During a study in the early stage of development, analytic software “MSC Nastran” that had been used by Komatsu was used. However, a large dissociation became visible between the analytical results and the test results with actual machines as the development advanced.

3.1 Limits with Nastran

The largest dissociation was the presence or absence of buckling. Whereas buckling was found in the location shown in Fig. 6 during a quality verification test, no such buckling was shown in the analytic results. The relationship between the jig stroke and load to the cab started to dissociate beginning at the location where buckling occurred (Fig. 6), finally presenting entirely different results that were unfit for practical use.

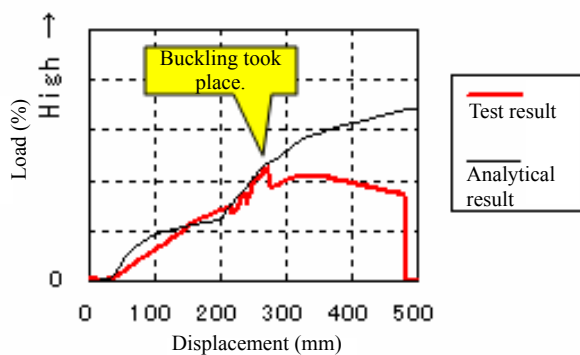


Fig. 6 Comparison of analysis by Nastran and test results

3.2 Change to PAM-CRASH

Realizing that the elasticity and plasticity analysis of cabs of hydraulic excavators, which were subject to buckling and large deformation, was not feasible using Nastran, analysis was started from the beginning using other software, PAM-CRASH. This software is suitable for the analysis of objects that are inflicted with large elastic-plastic deformation and rupture and has been used in other analyses. (For more information, see KOMATSU TECHNICAL REPORT 2003 VOL. 49 No. 151 “Simulation of Falling Object Protective Structure (FOPS).”)

4. Application Examples

4.1 Objects of Analysis

Analysis was conducted with the cabs of medium hydraulic excavators having a structure to protect the operator during tipping. The cabs were white bodies only provided with strength members and without external panels or other members.

4.2 Analytical Model

The shape of an analytical model was derived from 3D-CAD data, and the composite elements of each member were fabricated using “shell.” Shells are elements that have thicknesses and material properties as data and can suppress model volumes.

Peripheral parts other than the cabs to be evaluated can also be modeled. Also taken into consideration are the load and strain energy that are generated when a cab that is deformed by being pushed by a jig making contact with other equipment, such as the revolving frame, work equipment, or cylinder. Therefore, those elements that are estimated to make contact with the cab during analysis have to be prepared in advance (Fig. 7).

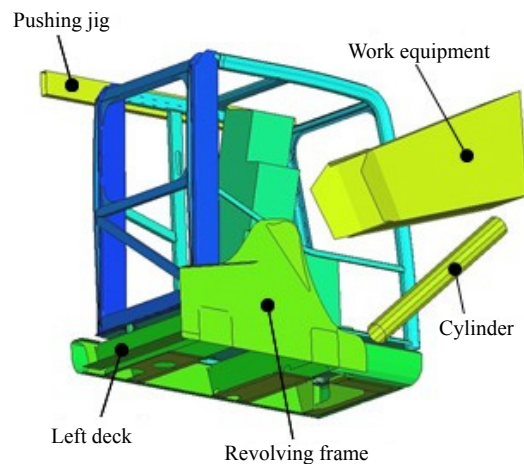


Fig. 7 Analytical model

4.3 Load

In addition to the lateral and vertical push conditions described in 2.1 and 2.2, simulation of deformation and distortion energy generated by pushing a pushing jig onto a cab to apply a load was performed. In this simulation, the following items require attention.

1) Avoiding generation of crash energy

The jig is placed as near to the cab as possible in advance to avoid large deformation by a crash when the jig and the cab make contact. The moving velocity of the jig is increased slowly after the jig makes contact with the cab.

2) Checking kinetic energy

A simulation of pushing a cab at the same jig velocity and mass density as those in a test that employs an actual machine would make the time needed for analysis unrealistically long (several months for lateral pushing only). For this reason, a technique called mass scaling is used to shorten the analysis time by increasing the mass density in addition to increasing the jig velocity. The jig speed and mass density are adjusted at this time so that the kinetic energy of the jig becomes sufficiently small compared with the distortion energy of the cab (quasi-static analysis) (Fig. 8).

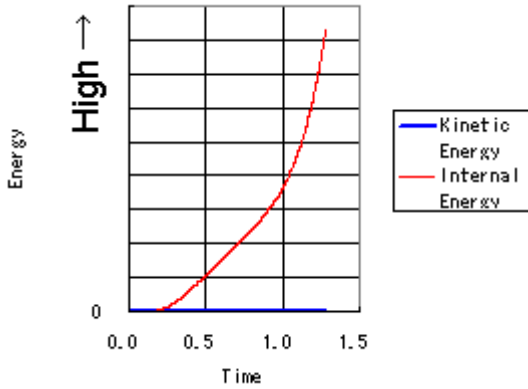


Fig. 8 Energy and time diagram

4.4 Analytical Results

The analytical results and bench test results obtained with an actual machine (hereinafter “bench test results”) are compared in the following using a medium hydraulic excavator under development as an example.

Cab deformation greatly differed from the bench test results in the initial stage of the analysis (Fig. 9), and analysis was conducted again after modifying the parameters of the analytical model.



Bench test result

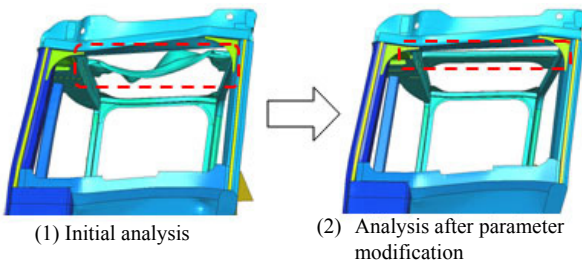


Fig. 9 Comparison of deformation

1) Initial analysis

[Lateral pushing conditions]

Compared with the results of the bench test, the peak of the load in the analytical results was about 20% higher (Fig. 10.a). This may be explained by contact between the right Pillar A and the work equipment when the absorption energy reached the target value, whereas the right Pillar A did not make contact with the work equipment in the bench test (Fig. 11).

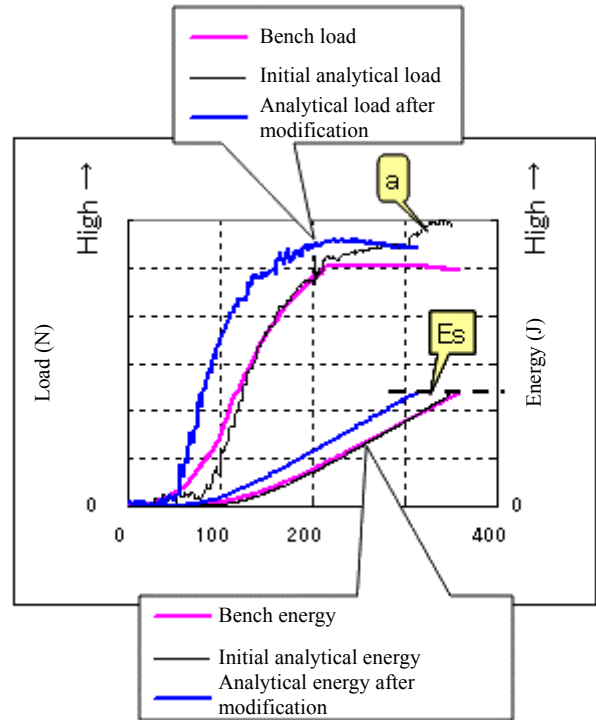


Fig. 10 Comparison of lateral push conditions

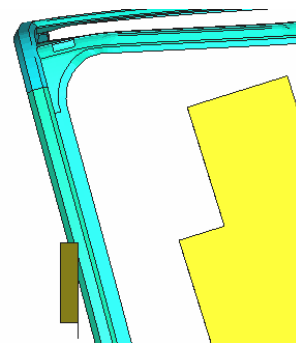


Fig. 11 Contact with work equipment during lateral pushing

[Vertical push conditions]

The results of both the bench test and the analysis met the criteria load. However, displacement of the jig in the analysis when the target load was met was about 26% larger than in the bench test. The shape after accomplishing the criteria load was different from the shape after the bench test.

4.5 Review of Modeling

The analytical model was modified as follows to eliminate dissociation between the bench test results and the analytical results.

- 1) Correction of clearance between cab and revolving frame
The clearance between the cab and the revolving frame was changed to that obtained in the bench test. The error seemed to have been made when the shape of the analytical model was simplified using a shell from 3D-CAD information prepared by the design staff (Fig. 12).

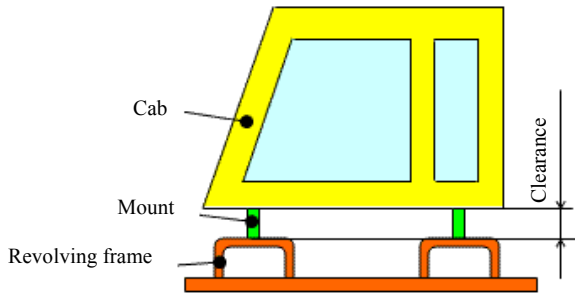


Fig. 12 Correction of clearance between cab and revolving frame

- 2) Addition of patch to revolving frame

In actual machines, a patch is welded onto the left main beam, and the patch made contact with the right rear of the cab during the bench test. This was not anticipated in the beginning, and the clearance was corrected fearing that both lateral and vertical push conditions might be causing some impacts (Fig. 13).

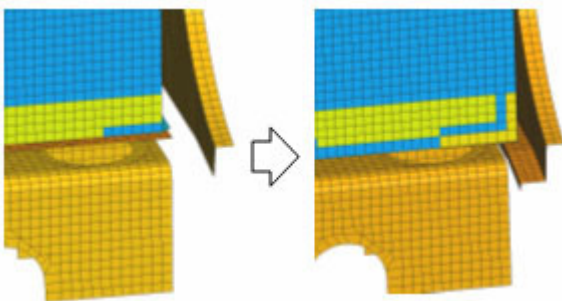


Fig. 13 Patch added to analytical model

- 3) Addition of damping

The analysis was a quasi-static analysis, the time to continue pushing the jig was long, and mass scaling was used to shorten the analysis time. For these reasons, vibration components such as noise that do not usually cause impacts were amplified, thereby causing unnatural behaviors. (Deformation continued even though the load by the pushing jig was reduced to “0” after the criteria energy was accomplished.) As a countermeasure, a parameter, damping ratio $\zeta = 0.1$, was added to the shell material information.

4.6 Results after Model Modification

Analysis was conducted again incorporating the review items described in 4.5. The results of the new analysis are as follows.

The problem of an abnormal increase of load (contact between the cab and work equipment) under the lateral push condition (Fig. 10.a) was solved.

Under the vertical push condition, cab deformation approached the bench test results compared with the initial analysis. However, jig displacement when the goal was accomplished dissociated more significantly than in the initial analysis and was “lenient” compared with the bench test results.

Analysis of vertical push load is performed in succession for analysis of deformation after a lateral push. The moment (M_0) applied to the base of the center line of a cab under the vertical push condition is therefore affected by the shape after the sideways push. The value of M_0 varies. Reproduction of the vertical condition is more difficult than under the lateral push condition (Fig. 14).

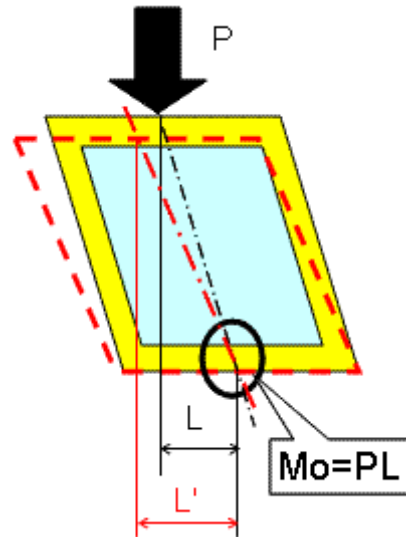


Fig. 14 Moment applied to cab during vertical pushing

5. Utilization of Analytical Results

Prior to feeding back analytical results to design, the following items need be judged by designers.

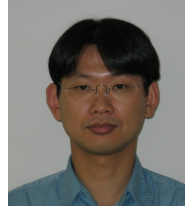
- 1) Check of locations with probable rupture
It should be noted that rupture in a cab undergoing plastic deformation during a bench test throws the rigidity off balance so that the load decreases suddenly. In forecasting a rupture location, stress values and strains are checked in the analytical data, and rupture can be ruled out if their values are less than a certain level.
- 2) If a location is found as a possible rupture location
Change the design of the probable rupture location, while at the same time modifying the analytical model and making recalculations. Change the design until rupture no longer occurs.

6. Future Challenges

Analysis at present has the following problems, and an effort will be made to improve and solve them.

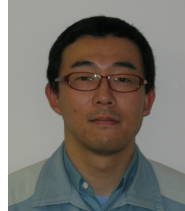
- 1) Analysis at present takes only yield, plasticity, and buckling into consideration and does not yet reproduce “rupture.”
- 2) Analytical results tend to be “lenient” compared with bench test results in both lateral and vertical push condition tests. Caution will be needed when they are used in designs that pursue optimization of cost reduction and strength assurance to the limit.
- 3) The lead time from the fabrication of an analytical model until analytical results are obtained is long. The process of fabricating shell models from 3D-CAD data for analytic purposes creates a bottleneck.

Introduction of the writers



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[A few words from the writers]

Needless to say, accuracy of analysis is important. However, the necessity of shortening the lead time needed for analyses was keenly felt especially in the foregoing task. It is virtually impossible to evaluate by manual calculations as quality verification is involved. Components to be designed were “cast or formed components” and the designers had to anxiously wait for the analytical results. This area, too, should be improved in the future.

[Notes]

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“MSC Nastran” is a registered trademark of MSC Software Corporation.