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Strength analysis of energy absorbing protective structure for excavator

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Abstract: Roll-over protective structures (ROPS) are essential safety features for excavators, particularly when operating on slopes. The load testing of ROPS systems for certification is mandated by ISO 12117-2 requirements. However, hydraulic excavators' attachments affect the required performance capability of the ROPS, making the evaluation process complex. This study presents a methodology for evaluating the strength of hydraulic excavator ROPS using numerical analysis. Nonlinear finite element analysis using ABAQUS is performed to assess the safety of the ROPS according to ISO standards, reducing time and costs by minimising the number of physical tests required. The structural strength analysis of the ROPS involves nonlinear contact, buckling, and large deformation, solved through quasi-static analysis and penalty method. Lateral, longitudinal, and vertical loads are performed, and the results show a good correlation between finite element analysis and bench test results. The study validates the FEA methodology for hydraulic excavator ROPS and provides a framework for performing strength tests on protective structures using numerical analysis methods.

Keywords: hydraulic excavator; ROPS; roll-over protective structure; energy absorption; Quasi-static analysis.

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1 Introduction

Excavators are one of the construction machineries. They are mainly used in harsh environments such as civil or construction sites; excavation works for digging the ground, loading work for soil, crushing works for dismantling the buildings, and flattening work for arranging the ground. The operator needs a structure that can provide a seat in a closed space and protect the driver from unexpected accidents such as falling of heavy objects, sand, rock, etc., and rolling-over equipment on a slope during operation of the machine. This structure is called a roll-over protective structures (ROPS) (ISO 12117-2, 2008; Wang et al., 2011). The ROPS system is intended to protect the space defined by the deflection limiting volume (DLV) as a living space for an operator wearing a seat belt when the machine is rolled over (Karliński et al., 2013; Clark et al., 2008). Currently, many organisations specify standards for ROPS testing, like International Organization for Standardization (ISO), Society of Automotive Engineers (SAE), Norma Brasileira (NBR), and Organization for Economic Cooperation and Development (OECD). They are all similar and consist of applying lateral load, longitudinal load and vertical load of the structure (Cesa and Oliveira, 2013). When the ROPS is plastically deformed, the ROPS decreases in energy and does not absorb energy gradually. If the energy absorption coefficient is insufficient, cracks can occur at the joints between components, which can cause the entire ROPS to collapse (Wang et al., 2009). Potential energy reduction during equipment rollover is proportional to energy absorption. Tests derived from this basis are defined as parameters such as energy and force and are determined by the equipment mass. This is because the mass of the equipment generates the energy that the ROPS must withstand (Alfaro et al., 2010)

In recent years, finite element analysis (FEA) technology has been developed to predict the nonlinear response of structures. However, more economical certification of ROPS using FEA method is not permitted by ISO standards (ISO 12117-2, 2008). If the appropriate ROPS FEA method is presented and utilised at the development stage, it will reduce the cost of repeated test and design changes before ISO certification. Previously, ROPS studies are performed exclusively for testing equipment without contact with other attachments, such as wheel loaders, tractors and mining equipment not affected by other factors during ROPS tests (Chen et al., 2012; Karliński et al., 2008; Clark et al., 2011). These machines have no difficulty in convergence because they do not contact with other attachments during ROPS FEA (Arana et al., 2008; Clark, 2005). However, in hydraulic excavators, they are difficult to converge due to contact with rigid bodies such as boom and hydraulic cylinder which affects ROPS performance. Due to this convergence problem, it is difficult to find a paper that performed with the FEA the structural strength of ROPS by excavators. One study simulated the lateral load after replacing the contacts using spring elements and compared them with the bench test results (Srivastav, 2014). Contacts using spring elements cannot accurately simulate actual contact phenomena. Simulation using surface contact is accurate in ROPS behaviour, but it is difficult to converge due to contact problems.

In addition, it is not easy to ensure the reliability of the results by conducting simulations in all three directions load. Therefore, there are no studies that simulated all three directions load in the reference. In this study, the excavator is a model belonging to a medium and large segment. It is tested according to ISO 12117-2. Considering the nonlinear characteristics of the contact structure, the problem caused by contact is solved using the commercial ABAQUS FEA program. The model contact used the surface contact to predict the behaviour of ROPS. Through this analysis, the structural strength of the ROPS in lateral, longitudinal and vertical directions is analysed and the validity of the FEA of excavator ROPS is verified by comparing FEA results with the bench test results.

2 ISO requirement

"ISO 12117-2 Roll-over protective structures (ROPS) for excavator of over 6 ton" is characterised by large attachments of hydraulic excavators unlike the "ISO 3471 roll-over protective structures (ROPS) for earth-moving machinery".

During the test, all structures that can contact the ROPS due to the deformation of the ROPS should be included. The boom and arm cylinder should be at the lowest height position on the ground reference plane (GRP) with the arms and buckets unfolded to the position where the ends of the bucket can reach the farthest point (ISO 12117-2, 2008), Where h is minimum boom height (mm) and r is maximum reach on the ground (mm). The application procedure of the load test is preceded in the order of lateral, longitudinal, vertical direction as shown in Figure 1. Lateral and longitudinal direction requires energy absorption. In the case of the lateral loading, the force may be significantly exceeded before the energy requirement is achieved, but the load must be maintained until the energy requirement is achieved or exceeded. The energy and force required by ISO 12117-2 is determined by the following equations (ISO 12117-2, 2008):

$$U_s = 13{,}000 \times \left(\frac{M}{10{,}000} \right)^{1.25} \tag{1}$$

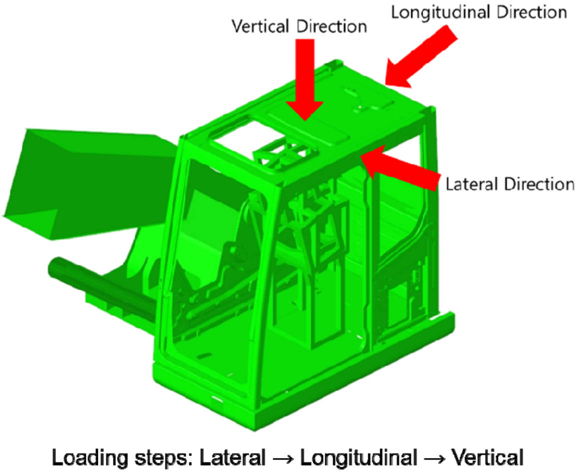
$$F_s = 35{,}000 \times \left(\frac{M}{10{,}000} \right)^{1.2} \tag{2}$$

$$U_f = 4{,}300 \times \left(\frac{M}{10{,}000} \right)^{1.25} \tag{3}$$

$$F_v = 12.75 \times M \tag{4}$$

where M is a maximum operating mass of the machine, U_s is lateral load energy [J], F_s is lateral load force [N], U_f is longitudinal load energy [J] and F_v is vertical load force [N].

Figure 1 Loading directions of ROPS test (see online version for colours)



The energy U is calculated using the following equation (ISO 12117-2, 2008):

$$U = \frac{\Delta_1 F_1}{2} + (\Delta_2 - \Delta_1)\frac{F_1 + F_2}{2} + \cdots + (\Delta_N - \Delta_{N-1})\frac{F_{N-1} + F_N}{2} \tag{5}$$

where Δ is deflection [mm], U is energy [J] and F is force [N]. The test is terminated if any part of the ROPS is invaded DLV before the required energy and force is achieved.

Table 1 Material properties of SCP10

Load direction	*Force* (N)	*Energy* (J)
Lateral	166,597	66,035
Longitudinal		21,842
Vertical	467,925	

The excavator model used in bench test and FEA is a model with a mass of 36,700kg. The force and energy that the ROPS system must resist without penetrating any part of the DLV as given in Table 1.

3 Simulation modelling

Excavator ROPS uses a variety of materials. The main material most commonly used among various materials is the A500 steel, and the strength characteristics of this material is written in Table 2.

Table 2 Material property of ROPS structure

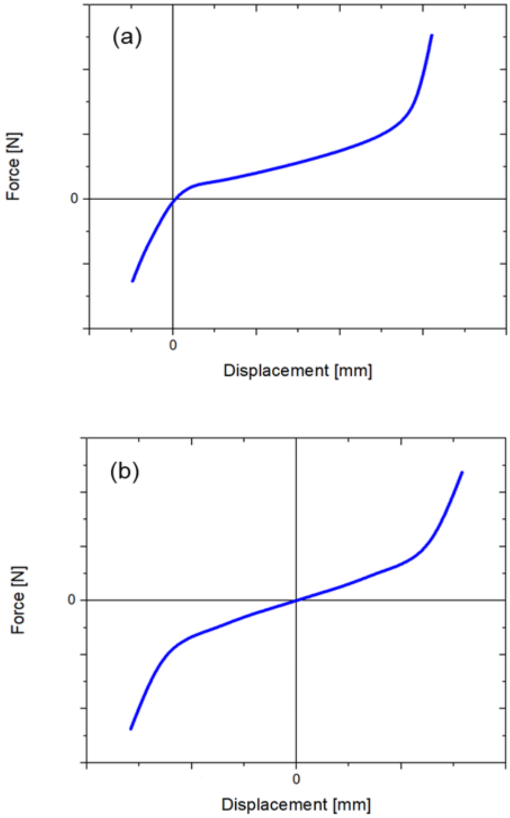
Material	*Density* (kg/m³)	*Yield limit* (MPa)	*Tensile strength* (MPa)	*Elongation* (%)
A500 steel	7800	270	310	25

The numerical analysis is performed step by step using the finite element method. Each part is modelled as a shell element and the element type is S4R (4-node general-purpose shell, reduced integration with hourglass control, finite membrane strains (Smith, 2017)). The S4R element is a 4-node shell element with 6 degrees of freedom per node. This is based on the first-order shear deformation theory and shows excellent performance in large deformation analysis. It is included in the universal element category and is suitable for thick and thin shell and plate construction. In addition, the cost of computation is reduced due to the reduced size of the analysis time to solve the same problem as the solid element (Khalili et al., 2011). The total number of element models used in the FEA is 276797, and the element size is modelled at ROPS 10mm and the frame parts 20 mm.

The four mounts supporting the excavator cabin on the upper frame have much work time and computation time when FE modelling the actual shape. Therefore, the connector elements are used to simulate the translational motion characteristics of ABAQUS for shortening the analysis time and simplifying the modelling. Figure 2(a) and (b) are nonlinear force-displacement data of a single mount obtained by compression-tension and shear tests. The X axis is displacement and the Y axis is force. The displacement range above the tested area is arbitrarily set assuming linearity. The load in the shear direction of the mount is stiff compared to the vertical direction.

In ABAQUS, the pressure-overclosure model uses hard contact as the basis. The stress at the contact surface is 0 before contact and the contact stress is applied at the moments of contact. At this time, it is considered that there is no penetration and the contact stress is infinitely increased theoretically (ABAQUS Analysis User’s Manual, 2017). In the case of excavator ROPS, contact stress is generated by contact with other attachments and its value is very large, which makes it difficult to converge in the analysis. Because of this problem, the softened contact methods allow penetration by numerical methods approximating hard contact. One of the softened contact methods, penalty method, is used to solve the contact problem. The difficulty of solving this contact problem is to determine the penalty stiffness scale factor which affects accuracy and stability. If the penalty stiffness scale factor is too high, the spring increases the total stiffness acting on the interface node. The penalty stiffness scale factor increase may cause a numerical error by reducing the stable time increment. Conversely, if the penalty stiffness scale factor is too small, excessive node penetration and false stick region estimation may occur, resulting in incorrect results (Meo et al., 2013). The analysis is repeated several times to use the correct penalty stiffness scale factor. Penalty stiffness behaviour is set to be linear, and the penalty stiffness scale factor is set to 1 for general contact areas, but the penalty stiffness is set to 0.8 for the large contact stress areas, which improves the convergence of the analysis. Also, the excavator ROPS has a nonlinear problem due to friction between the boom and other attachments. In addition, it is difficult to solve this problem in the static analysis because the contact part and the alongside structures are buckled and excessively deformed. In this study, the static instability of the structure due to buckling and excessive deformation is analysed with the dynamical conception of quasi-static approach. Quasi-static analysis, however, ignores dynamic effects and assumes that the object is in a static state. Consequently, there should be little or no dynamic impact. Therefore, the kinetic energy value must be less than 5% of the internal energy value to be reliable.

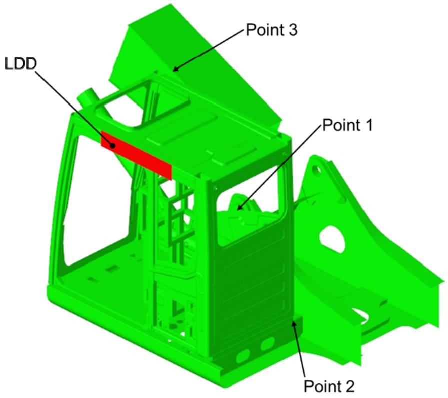
Figure 2 Test results of cabin mount: (a) tensile and compression direction and (b) shear direction of ROPS test (see online version for colours)



4 Result and discussion

Simulation is performed according to the test methods and procedures specified in ISO 12117-2. The maximum energy to be absorbed and the maximum force to be resisted are set based on the weight of the equipment, and the energy and force requirements at each step are achieved or exceeded in Table 1. Lateral load application is performed until force and energy are achieved. However, both are not required to be satisfied and must be performed until energy is achieved or exceeded. In most cases, the force is first satisfied and continue until the energy is achieved. The load is applied to the load distribution device (LDD) installed in the ROPS as shown in Figure 3.

Figure 3 Lateral load distribution device (LDD) and contact points (see online version for colours)



Contact process: Point 1 → Point 2 → Point 3

This is an 800 × 150 mm and 15 mm thick plate. The lower of the frame is fixed. The length of the load distribution plate is limited to 80% of the length of the side ROPS by the ISO standard. The load application is also applied within the DLV front and back interface. When a load is applied to the ROPS, the cabins show nonlinear behaviour due to the mounts between the cabin and the upper frame, and contact occurs in the order of points 1, 2 and 3 in Figure 3.

The deformation of the A pillar in Figure 4 occurs due to contact with the boom. The load from the lateral direction is supported by the contact between the right A-pillar and the boom. After the boom contact, the buckling and large deformation occur in the ROPS system. Figure 5 shows a C-pillar with buckling. At the beginning of the contact in the A-pillar, the force of resistance is large, and the amount of resisting force decreases as plastic deformation occurs in the A, C pillars. Figure 6 shows the overall deformation and stress of the lateral applied load in the lateral direction. Figure 7 compares the bench test results with the simulated results of the lateral load test on a hydraulic excavator ROPS system. The lateral load ISO criteria is selected based on the weight of the equipment as described above. The force requirements are achieved first and then the load is continued until the energy requirements are met. In the bench test, the energy requirement is achieved at about 490 mm, whereas in the simulation, the energy requirement is achieved at about 500 mm. Both results are 97% correlation. Slight differences in the results are considered due to variables such as component assembly tolerance in the bench test. It is also considered because the material properties are not the same. When lateral energy requirement of equation (2) is achieved, the applied load is removed for ROPS spring back. Once the ROPS completes the spring back, the load is applied in the longitudinal direction. The load is applied until the energy requirement is met or exceeded and applies the load from the rear along the centreline of the load application position in the lateral direction. The longitudinal load distribution plate is limited to within 80% of the length of the rear ROPS. The analysis time is shortened by removing unnecessary elements such as boom and hydraulic cylinder of hydraulic excavator which does not affect ROPS performance when applying longitudinal direction load. Also, stress and strain due to the application of lateral load in the previous step must remain in the initial state of the simulation when applying the load in the longitudinal direction. Figure 8 shows the longitudinal direction of the LDD. This is a 480 × 185 mm and 15 mm thick plate, with two plates connecting the cabin to the LDD.

Figure 4 Results of A-pillar after the lateral loading: (a) actual bench test and (b) FEA (see online version for colours)

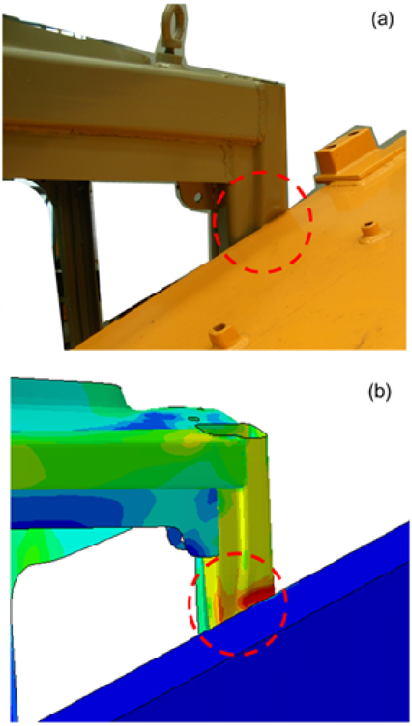


Figure 5 Results of C-pillar after the lateral loading: (a) actual bench test and (b) FEA (see online version for colours)

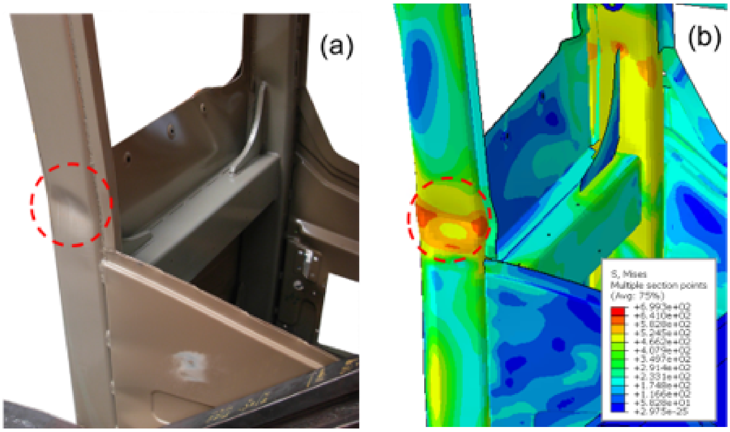


Figure 6 Deformation and stress produced to lateral loading in ROPS of excavator (see online version for colours)

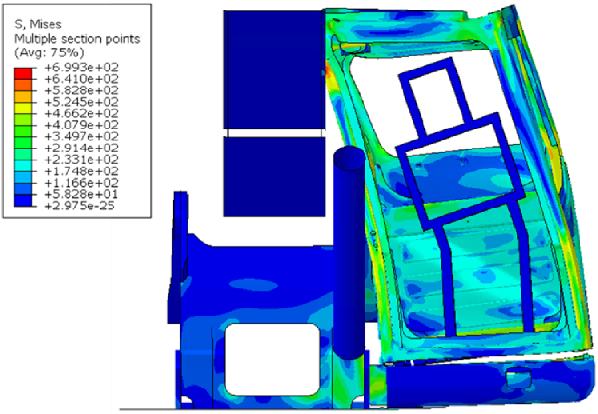


Figure 7 Results of lateral loading: (a) energy-displacement and (b) force-displacement (see online version for colours)

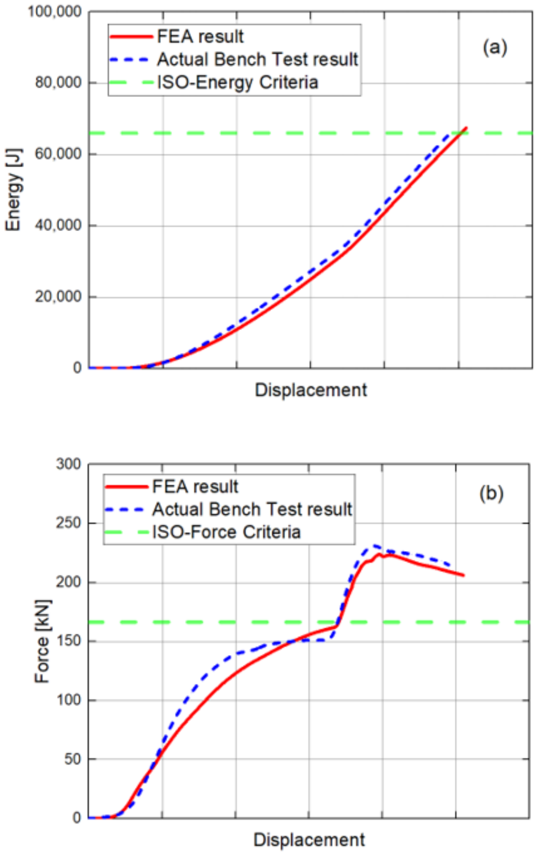
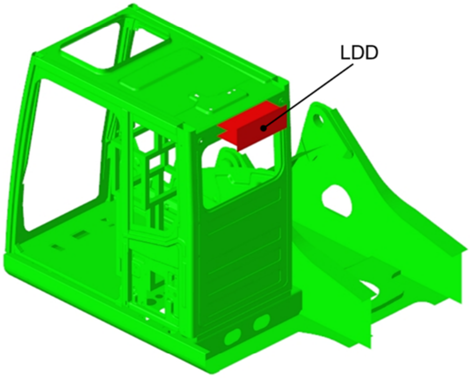


Figure 8 Longitudinal load distribution device (LDD) (see online version for colours)



The longitudinal LDD is deactivated to avoid affecting the lateral direction analysis results at the previous analysis steps. The longitudinal LDD is activated for loading at the longitudinal direction analysis step.

Figure 9 shows the overall deformation and stress of the longitudinal applied load in the longitudinal direction. First, the bottom of the A pillar contacts the upper frame. Then, as the top of the cabin moves in the front direction, deformation occurs in the pillar. Figure 10 compares the bench test results with the simulation results of longitudinal load tests on a hydraulic excavator ROPS system. Likewise, the longitudinal load ISO criteria is selected based on the weight of the equipment as described above. The load is applied until the energy requirement is achieved. In the bench test, the energy requirement is achieved at about 280 mm, whereas in the simulation, the energy requirement is achieved at about 277 mm. Bench test results and simulation results showed 96% correlation. The reason for the difference between the bench test result and the FEA result is considered due to that the material properties is not exactly same. Because of these material properties differences, the result difference in the lateral direction simulation is caused by accumulating the result difference of the longitudinal direction simulation.

Figure 9 Deformation and stress produced to longitudinal loading in ROPS of excavator (see online version for colours)

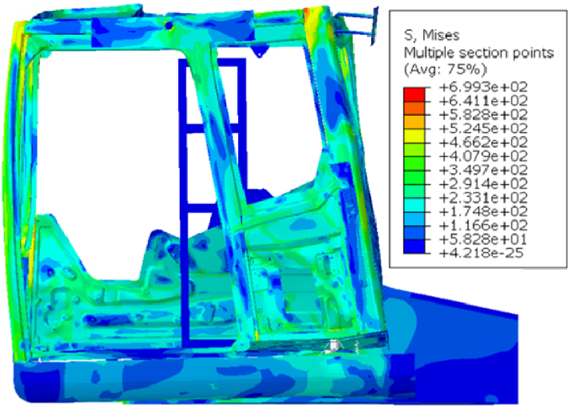
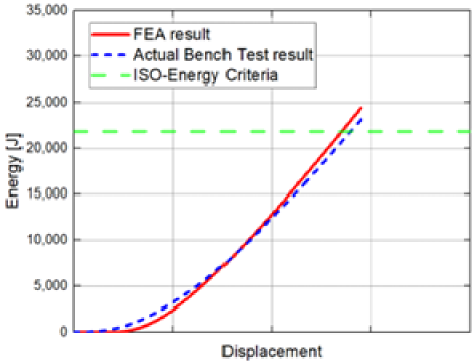


Figure 10 Result of longitudinal loading energy-displacement (see online version for colours)



When the longitudinal energy requirement of equation (3) is achieved, the load applied is removed for ROPS spring back. Likewise, the analytical results of the application of lateral and longitudinal loads should remain in the initial state of the load application simulation in the vertical direction. When the elastic restoration is completed, apply the load in the vertical direction. The load application position shall be applied to the plane perpendicular to the longitudinal centreline of the structure before the ROPS is deformed. The vertical direction applies the load until the force requirement is achieved or exceeded, and there is no limit to the LDD. Figure 11 is the vertical direction LDD applied to the ROPS structural strength simulation. The vertical LDD is a 2500 × 400 mm and 30 mm thick plate. The vertical LDD is activated in the vertical direction analysis step. The LDD falls vertically and contacts the ROPS to transfer energy. The ROPS absorbs this energy.

Figure 11 Vertical load distribution device (LDD) (see online version for colours)

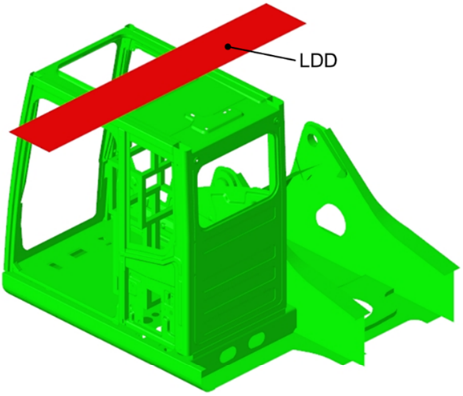


Figure 12 shows the overall deformation and stress of the applied load in the vertical direction. During the vertical direction test at the point 1 and 2, the frame is in contact with the ROPS, which supports the load in the vertical direction. Figure 13 compares the results of bench tests with the results of a vertical direction load test on a hydraulic excavator ROPS system. Like the preceding, the vertical load ISO criteria is selected based on the weight of the equipment as described above. The vertical direction loading is applied until the force requirements are achieved and the force requirements are achieved at about 67 mm in the bench test and the force requirements are achieved at about 73 mm in the simulation results. The good correlation between the two results is approximately 82%, although there is less correlation than the simulation results in the two directions performed previously.

Figure 12 Deformation and stress produced to vertical loading in ROPS of excavator and contact points (see online version for colours)

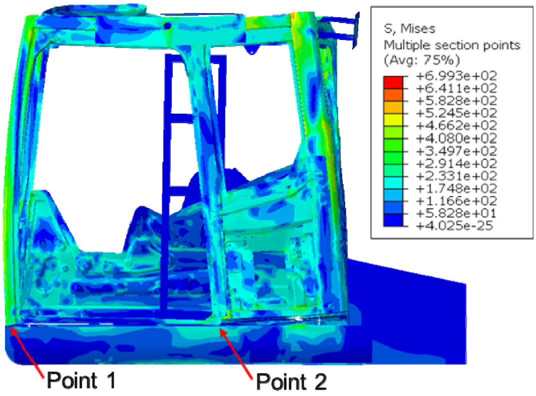
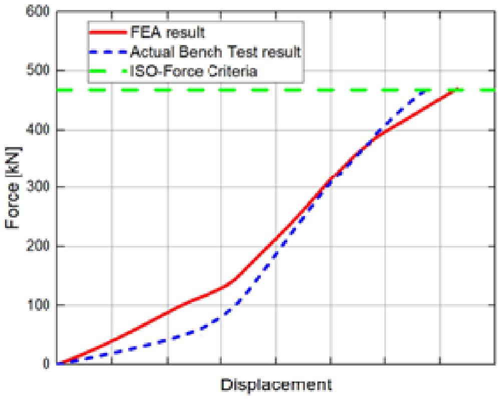


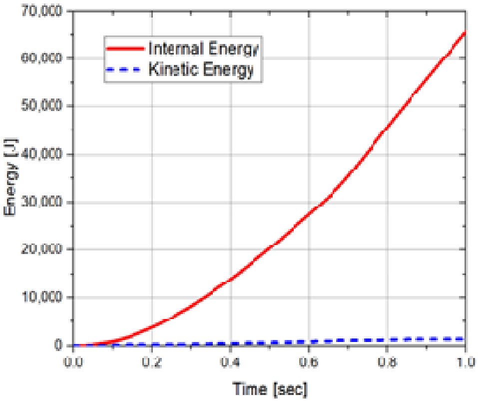
Figure 13 Result of vertical loading force-displacement (see online version for colours)



The reason for the difference between the bench test result and the FEA result is considered due to that the material properties is not exactly same. Because of these material properties differences, the result difference in the lateral and longitudinal directions simulation is caused by accumulating the result difference of the vertical direction simulation. When the vertical force requirement of equation (4) is achieved, the simulation is terminated.

Finally, the operator's survival space DLV is not invaded by the ROPS in three stages of lateral, longitudinal, and vertical directions, and space is secured. The results of the analysis show that the simulation shows that the model's total kinetic energy to internal energy ratio is less than 2% as shown in the following Figure 14. This indicates that the quasi-static simulation is accurate and acceptable.

Figure 14 Results of internal energy and kinetic energy (see online version for colours)



5 Conclusions

Numerical analysis is performed using ABAQUS, a nonlinear finite element solver, to evaluate the safety of hydraulic excavator roll-over protection structures according to the ISO standard. Structural strength analysis of hydraulic excavator ROPS system has convergence problem due to nonlinear contact, buckling, and large deformation, and solved through quasi-static analysis and penalty method. In addition, the accuracy of the following factors is very important for the FEA results to have a good correlation with bench test results. The accuracy of the material properties obtained through the tensile test is very important, and the nonlinear load-displacement value obtained through the load test of the mount is also important. In addition, appropriate penalty stiffness coefficients can be used to improve the convergence and accuracy of analysis. Finally, the bench test conditions and the FEA conditions are set as identical as possible. In future studies, the accurate material properties of all materials configuring ROPS will be applied to obtain better results. The lateral load, the longitudinal load and the vertical load are all performed, and the good correlation between the FEA results and the bench test results is verified and the feasibility of the FEA method for the hydraulic excavator ROPS system is verified. Using this methodology, it will be possible to shorten the development period and reduce the development cost by minimising the test for evaluating the ROPS system which takes time and cost in the development stage.

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