Progressive damage modeling of CABIN for the validation of roll-over protective structure (ROPS) with testing results.

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Abstract*: CAE has been an important tool in the process of construction and off-highway vehicles product development. Cabin strength of these machines are evaluated for roll-over protective structure (ROPS) and falling object protective structure (FOPS) to provide the operator safety. Testing is performed on the cab structure to achieve the static loading criteria under ROPS and dynamic loading criteria under FOPS based on standards like ISO 3471.*

The scope of this paper is to develop a simulation methodology for correlating the Testing results with FEA results. Cabin structure requires ROPS and FOPS validation before the actual mass production. The structure under test should pass the ROPS criteria for the force and energy requirements as defined in the standards, even with large induced plastic deformation and/or a developed and propagated crack. In case of developed crack, the loss in stiffness from the crack affects the load deflection characteristic of the structure. This simulation methodology would help in predicting the possible failure location which may be critical during the design of the structure.

Finite element modeling, without taking into account the lost stiffness due to developed crack, over predicts the load carrying capability of the structure. Abaqus offers a general framework for material failure modeling to account for the degradation of stiffness under developed crack. The present work uses the Abaqus progressive damage and failure modeling technique to validate the test with FEA. The results of these simulations show good correlation at the failure location as observed during the Testing.

Keywords*: ROPS, FOPS, Crack Initiation, Crack Propagation, Progressive Damage, Failure, Abaqus, ISO standards*

1. Introduction

Roll over Protective Structure is a system of structural members whose primary purpose is to reduce the possibility of a seat-belted operator being crushed during the machine roll over. ROPS is a system that consists of the ROPS structure (or cab with an integrated ROPS), mounting system and frame. ROPS systems have relied almost exclusively on surrounding the operator (driver) by a frame or cab, strong enough to absorb the impact energy of an overturning vehicle without violating the DLV (Deflection Limiting Volume). This frame or cab is known as a ROPS (roll-over protective structure). The strength of the ROPS must be related to the weight of the vehicle (although different conditions apply in different sectors). Different standards are available for performing the ROPS Test (e.g. ISO 3471:1994(E)/SAE J1040 May 1994, EEC/79/622,ISO 8082:1994), according to the different purposes for which they are used.

ISO 3471 is the most prevalent standard for most types of earthmoving machinery. It specifies the structural performance requirements for a ROPS system. ISO 3471 requires a push test to certify a ROPS system. The requirements are force resistance in the lateral, longitudinal and vertical directions, and energy absorption in the lateral & longitudinal direction. The testing is conducted using these components. The energy requirement and limitations on deflection (DLV) under lateral loading are intended to ensure that the ROPS will deflect when it impacts a surface which will not significantly deform while retaining significant capability to withstand subsequent impacts in an overturn.

Acceptance criteria for test are specific lateral force and energy, longitudinal energy and vertical load-carrying capacity. There are limitations on the deflections of the structure so as no parts of the ROPS should enter the operator occupied area, also known as DLV (Deflection Limiting Volume). The ROPS structure may initiate and develop a crack during the course of test. The ROPS structure is considered to be acceptable even if there is crack, as long as the DLV is not violated before the Force/energy requirement is achieved.

Finite element simulations are most often used in the industry to validate the cabin structure for ROPS test. These techniques have added advantage when it comes to simulating destructive testing which reduces the lead time of product development cycle. During the testing of the cab structure cracks are observed at critical locations. The stiffness of structure reduces under developed crack. Finite element simulation without considering the loss of stiffness may not correlate well with the test results once a crack initiates and propagates in the structure. Abaqus offers a general framework for material failure modeling that allows the combination of multiple failure mechanisms acting simultaneously on the same material. Material failure refers to the complete loss of load-carrying capacity those results from progressive degradation of the material stiffness. The stiffness degradation process is modeled using damage mechanics. The stress-strain response, such as that illustrated in Figure 1, will show distinct phases. The material response is initially linear elastic, followed by plastic yielding with strain hardening. Beyond point "c" there is a marked reduction of load-carrying capacity until rupture. The deformation during this last phase is localized in a neck region of the specimen. Point "c" identifies the material state at the onset of damage, which is referred to as the damage initiation criterion. Beyond this point, the stress-strain response is governed by the evolution of the degradation of the stiffness in the region of strain localization. In the context of damage mechanics can be viewed as the degraded response of the curve that the material would have followed in the absence of damage initiation criterion. Beyond this point, the stress-strain response c – d is governed by the evolution of the degradation of the stiffness in the region of strain localization. In the context of damage mechanics c – d can be viewed as the degraded response of the curve c – d’ that the material would have followed in the absence of damage. Point “d” corresponds to deletion of element.

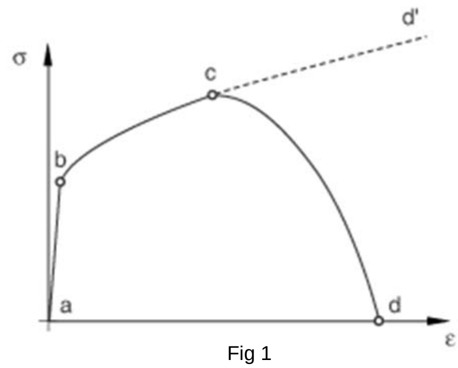

Fig 1

Stress-strain response of a metal specimen

a-b-c-d” effective (or undamaged) material response
c- Damage initiation
c-d Damage Evolution path

2. FEA Approach and Methodology

Cabin, upper frame (on which cab is mounted) and portion of boom is considered during the ROPS analysis. FE model is prepared in line with the Testing setup model. Cabin iso-mounts is modeled with spring element with non-linear properties. The sheet metal parts, like door frames (internal & external panel), roof panel are considered in the analysis and modeled with the shell element (S4). Pillars A, B & C are also modeled with shell elements. Uniform mesh is prepared at the expected failure location to capture the material damage effect. Expected failure location identified was the backing plate, cut-out at left c-pillar and at the junction of rear cross member with the C-pillar. Load application for Lateral and longitudinal is done by load distributor which is modeled with the high- stiffness bar element (B31). The span of the load distributor is decided as per the ISO parameters, Fig 2 and Fig 2.1 explains the FE Model setup for the analysis and Fig.3 provides the details for the load application methodology for Lateral and longitudinal/back loading using the line diagram. Vertical loading is simulated with the help of pressure plate which is dropped from the top of roof.

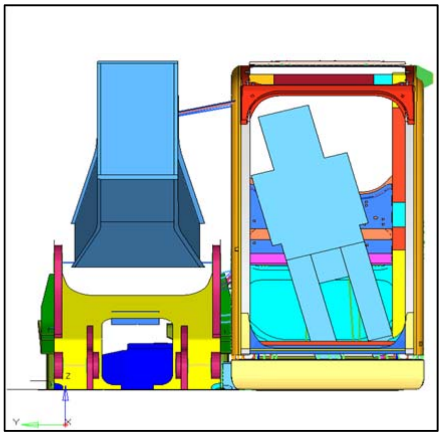

Fig. 2

FE Model Setup for analysis

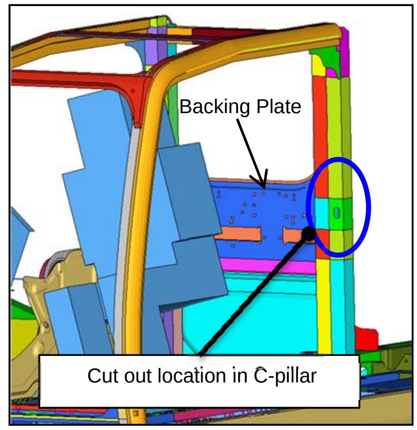

Fig.2.1

C-pillar cut-out Location

Contacts in the FE model are defined with the non-linear springs in order to reduce the computation time. Bi-linear stress-strain material data is defined for the components of cabin structure. Material damage property is defined to the c-pillar, backing plate & rear cross member, as crack was observed during the testing at these location. Material damage properties include damage initiation criteria, damage evolution law and no element deletion option. In the actual test, crack was also observed at the cut-out location of the C-pillar as shown in Fig. 2.1

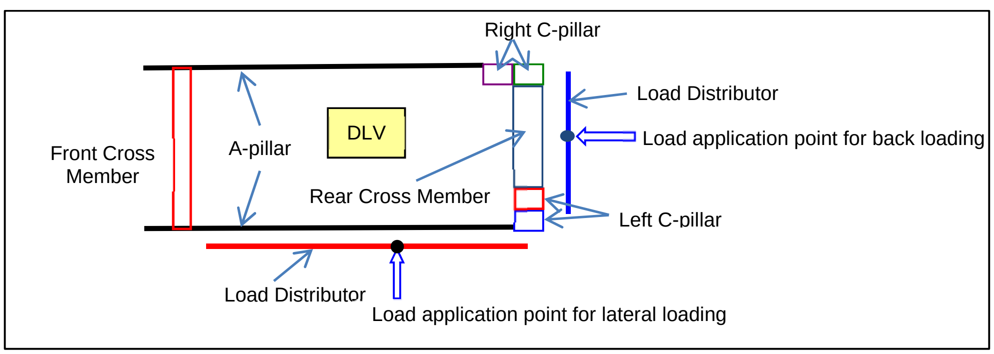

Fig 3

Load application methodology on Cabin (Line diagram)

2.1 Meshing Methodology

Special attention is taken while creating the mesh at the expected failure location. Uniform mesh density is created at failure location of backing plate and at the junction of the c-pillar and rear cross member. Fig 4(a) shows the mesh portion of rear cross member connection with left side c-pillar; Fig 4(b) shows the mesh portion of rear cross-member connection with right side c-pillar; Fig 4(c) shows the mesh portion of cut-out on the left c-pillar; Fig.4 (d) shows the mesh portion of backing plate.

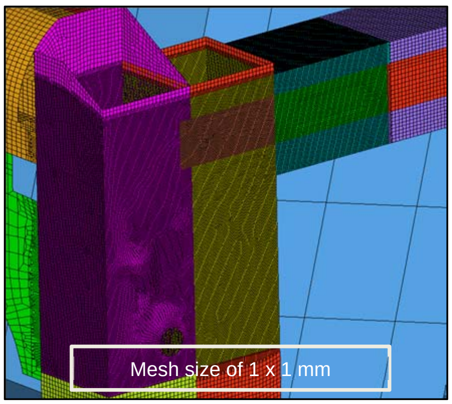

Fig.4 (a)

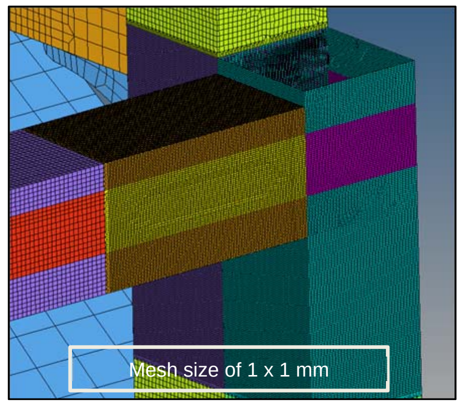

Fig. 4(b)

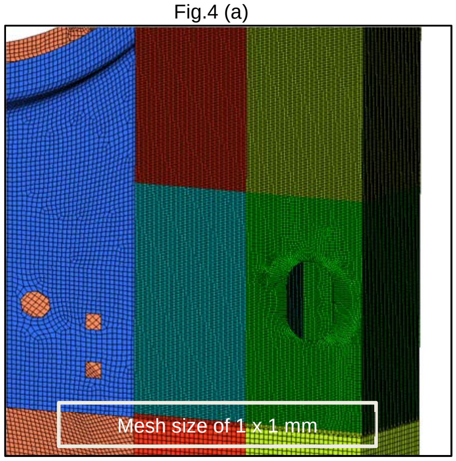

Fig. 4(c)

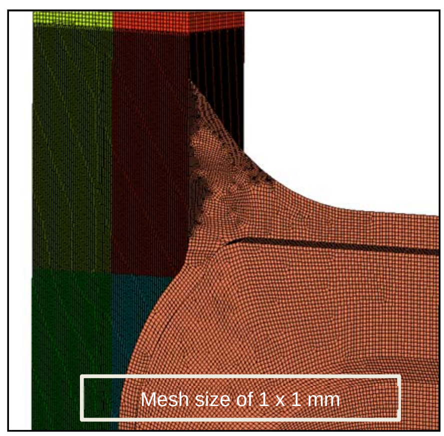

Fig. 4(d)

2.2 Material Definition

Bi-linear stress-strain material data is considered in the analysis due to unavailability of multi-linear data. At the predicted failure location material damage property, damage initiation and damage evolution is also provided.

Abaqus/Standard and Abaqus/Explicit offer a general capability for predicting the onset of failure and a capability for modeling progressive damage and failure of ductile metals.

- Undamaged elastic-plastic response of the material.
- Damage initiation criterion.
- Damage evolution response, including a choice of element removal.

There are various choices for damage initiation criteria for ductile metals, each associated with distinct types of material failure. They can be classified in the following categories:

- Damage initiation criteria for the fracture of metals, including ductile and shear criteria.
- Damage initiation criteria for the necking instability of sheet metal. These include forming limit diagrams intended to assess the formability of sheet metal.

Damage initiation criterion used in the present work is based on equivalent plastic strain for ductile fracture of metals. The ROPS test is performed to achieve static loading criteria. The stress-strain can be assumed to be rate independent under static loads. The strain-rate dependency of damage initiation equivalent plastic strain is neglected in the analysis. Sheet metals and posts materials have high ductility. Damage initiation equivalent plastic strain is assumed to be 70-80% of the fracture strain of the material.

In the present work the damage evolution is defined based on the equivalent plastic displacement. When material damage occurs, the stress-strain relationship no longer accurately represents the material's behavior. Damage evolution defines the post damage-initiation behavior of the material. At the point of crack initiation, the stiffness of the material starts to degrade. The material stiffness reduces as a result of softening of yield stress and degradation of elasticity. The rate of degradation of the material stiffness is defined using *DAMAGE EVOLUTION key word. The criteria for full degradation of any element can be defined using EFFECTIVE PLASTIC DISPLACEMENT (at the point of failure). With this approach, the softening response after damage initiation is characterized by a stress-displacement response rather than a stress-strain response.

When the damage initiation criterion is reached, the effective plastic displacement, $\overline{u}^{pl}$ is defined with the evolution equation

$$\overline{u}^{pl} = L\,\overline{\epsilon}^{pl}$$

L, is the characteristic length of the element

$\overline{\epsilon}^{pl}$, is equivalent plastic strain

Abaqus has the control over elements with severe damage to delete an element once maximum degradation is reached as defined by the user. In current work, damage value is considered to be 0.99. No element deletion option is considered during this analysis as allowing element deletion in the analysis results in severe convergence issues.

3. Simulation Technique

3.1 Loads and Boundary Condition

Load application for the ROPS model is as per the ISO criteria. For Lateral & longitudinal loading, enforced displacement is applied from the side and back as shown in the Fig.3 and for the Vertical loading the Pressure plate is used from top side of Cabin. Loading is applied sequentially on the structure.

3.2 Analysis Technique

In actual testing, load is applied slowly from side wards on A-pillar with the help of hydraulic ram on particular span in Lateral loading and on the rear cross member for back loading. In FE analysis, there is possibility of material failure during the loading due to the severe deformation of sheet metal parts in cabin and analysis may fail due to convergence issues. In this work, Quasi-static analysis was performed on the ROPS structure and by this method we can improve the convergence issue, due to buckling and excessive deformation of the sheet metal parts of the ROPS structure. This application introduces inertia forces to regularize unstable behavior. The analysis results show that the ratio of total kinetic energy of the model to internal energy was less than 3% throughout the simulation, which indicates that a quasi-static solution was accurate enough and acceptable.

4. Results and Discussion

Bench Test of the cabin model was not passing the acceptance criteria for energy during the lateral loading and several cracks was observed at various locations. Major crack was observed at the cut-out location on the left side C-pillar. The force deflection graph shows the major drop during the lateral loading. Initially, when FE Analysis was performed without considering the material damage modeling, no drop was observed in the Force-deflection graph and analysis cleared the acceptance criteria of force and energy. By considering the progressive damage and material failure modeling in the analysis, a clear observation of drop in Force-deflection curve was seen with crack location as similar to the actual bench Test model. In the FE analysis, with material damage modeling, crack was also observed at the cut-out location as same as in the actual bench test model. FEA and actual test graph is compared for without and with progressive damage and material failure modeling in Fig. 5(a) and Fig. 5(b). From the graph it is clearly observed that there is a good correlation of Test and FEA reault with progressive damage and material failure modeling technique. It also visualizes, the degradation in the stiffness is effectively captured in the progressive damage method then the normal analysis technique.

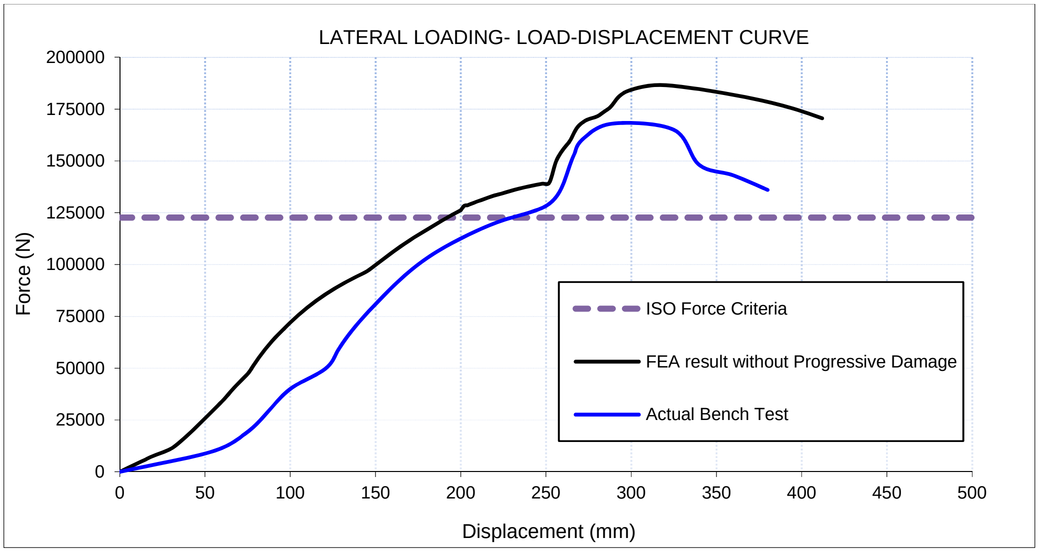

Fig.5 (a)

FEA graph without progressive damage & material failure modeling

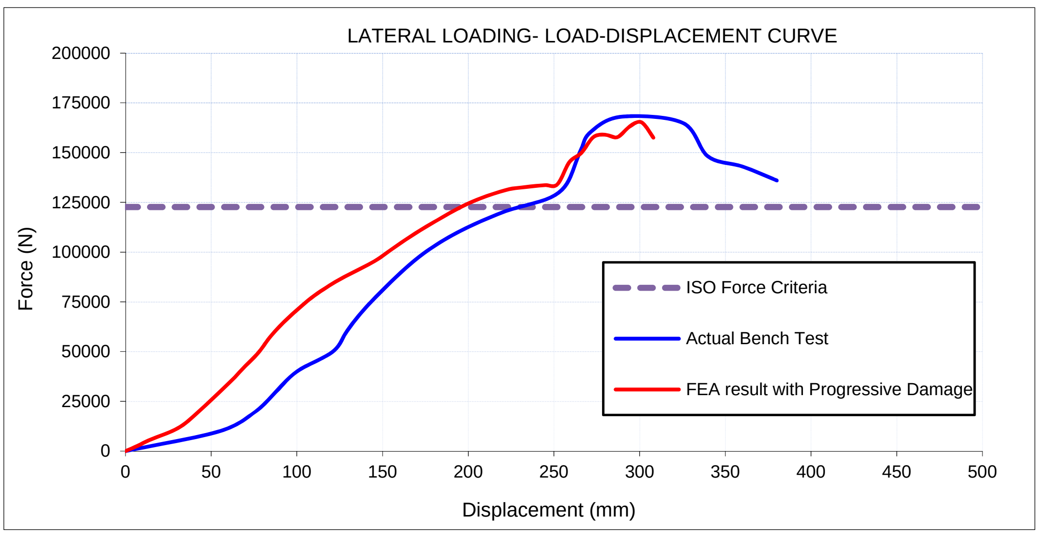

Fig.5 (b)

FEA graph with progressive damage & material failure modeling

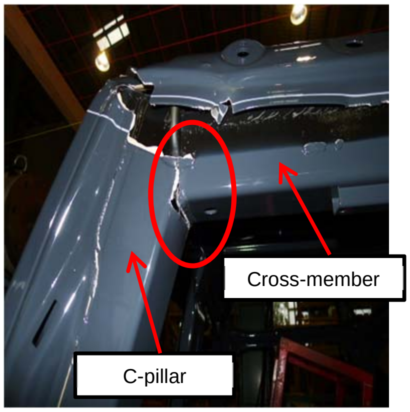

Fig. 6(a)

C-pillar & Cross-member connection

(Test Picture)

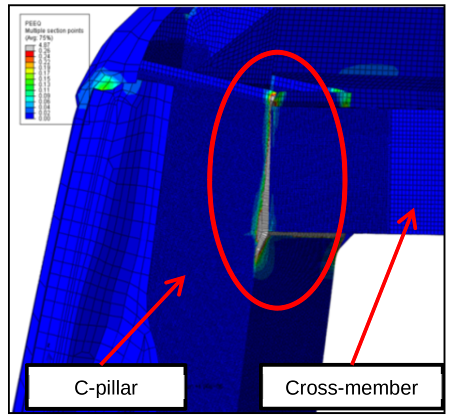

Fig. 6(b)

C-pillar & Cross-member connection

(FEA Result)

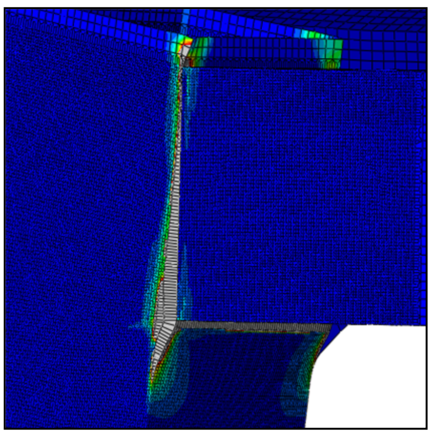

Fig. 6(c)

Exploded View of C-pillar & Cross member

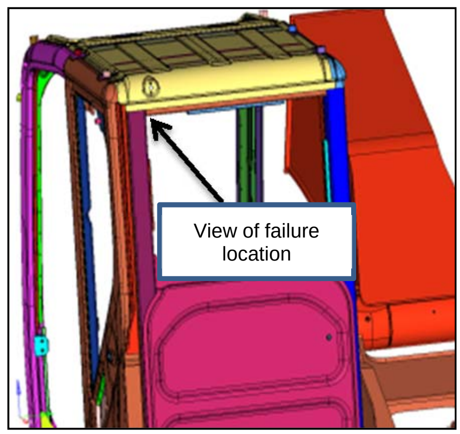

Fig. 6(d)

Location and result view description

Fig. 6 (a, b, c) provides the clear idea of the Failure location with progressive damage and material failure modeling technique. Good correlation of FEA and Test result is observed at the connection of C-pillar with the cross-member. The Failure observed in the actual model matches with the FEA result.

Fig. 7 (a)

Right C-pillar & Cross-member connection

(Test Picture)

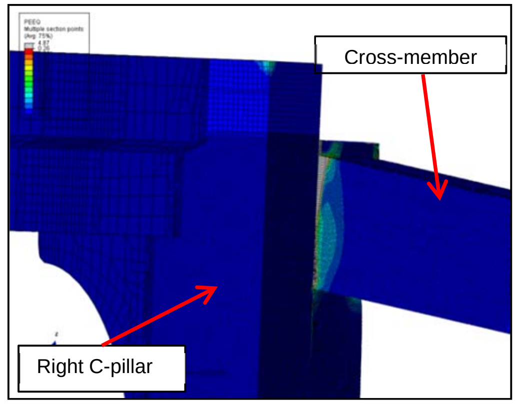

Fig. 7 (b)

Right C-pillar & Cross-member connection

(FEA Result)

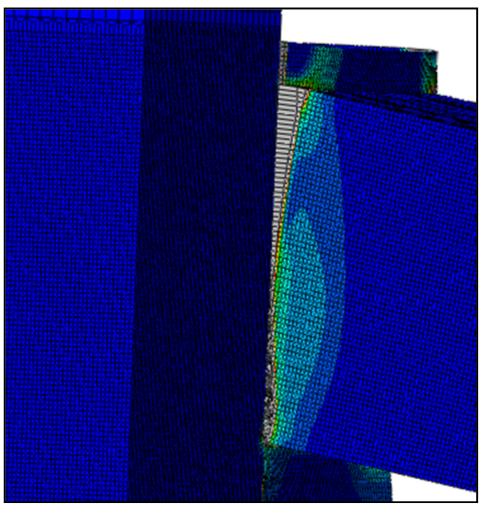

Fig. 7 (c)

Exploded View of C-pillar & Cross member description

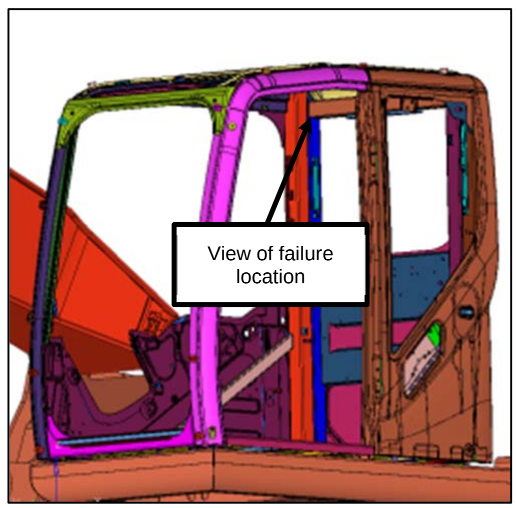

Fig. 7 (d)

Location and result view

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Fig. 8 (a)

Left C-pillar cut-out section

(Test Picture)

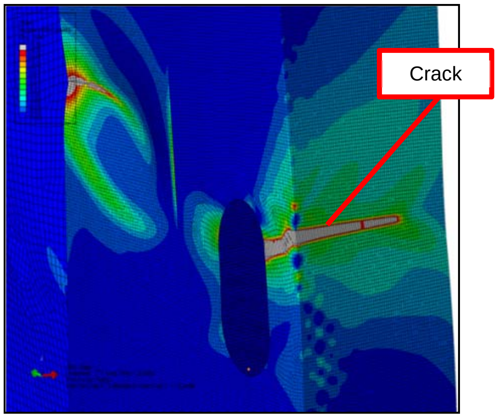

Fig. 8 (b)

Left C-pillar cut-out section

(FEA Result)

FEA results show the crack at the cut-out location same as observed in the Test model. The crack at the cut out location results in the degradation of the stiffness which is also reflected in the Force vs. Displacement graph. Advantage of using progressive damage material modeling technique will help in predicting the failure location prior to the testing.

5. Conclusions

According to the study and analysis results in the present work, the conclusions are summarized as following:

1. Good correlation of the Test and FEA result can be achieved and it will be useful in suggesting the design change for the failure location prior to the prototype testing.
2. Quasi-static analysis technique shows better convergence than the static analysis technique in case of the material failure or buckling of structure. ROPS consist of sheet metal parts at the side, back and roof, which undergoes severe deformation during the progress of analysis and sometimes it, is impossible to run the analysis in Static simulation.
3. Rate dependent stress-strain data should be used to simulate the exact behavior in the analysis.
4. Uniform mesh size should be provided at the predicted or assumed failure location to capture the decay in stiffness due to material failure.

6. References

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