

Overhead Guard Physical Tests vs LS-DYNA FE Simulations

Janka Cafolla and Derick Smart
Tata Steel UK Limited

Barry Warner
Hyster-Yale UK Limited

ABSTRACT

The lifting and excavating industry are not as advanced as automotive in the use of modern CAE tools in the early stages of design and development of heavy machinery. There is still a lack of confidence in the integrity of the results from FE simulations and optimisation and this becomes a barrier to the adoption of virtual prototyping for vehicle verification. R&D of Tata Steel has performed tests on two forklift truck overhead guards supplied by a major manufacturer. Based on the international standard for Falling Object Protective Structures (FOPS) as an initial input to the method of testing, the main aim of this study was to generate as much test data as possible to correlate the Finite Element (FE) simulations of two tests - a static and a dynamic test. The static test was developed to deform the overhead guard plastically in a slow controlled manner, so it would be easier to correlate the measured data to FE simulation. A dynamic test is always very difficult to correlate due to the fact that the whole test is over in less than a second and the dynamic response of the structure makes the data extremely noisy. However, this paper demonstrates that paying close attention to all of the input data for an FE model results in a close correlation between the test and the FE simulation even in highly dynamic conditions.

CITATION: Cafolla, J., Smart, D., and Warner, B., "Overhead Guard Physical Tests vs LS-DYNA FE Simulations," *SAE Int. J. Commer. Veh.* 9(2):2016, doi:10.4271/2016-01-9017.

INTRODUCTION

ROPS, FOPS and TOPS are well known acronyms in agricultural, material handling, mining and construction industry. Roll Over; Falling Object and Tip Over Protective Structures have to be used as appropriate in all tractors, combine harvesters, forklift trucks, bulldozers, excavators, compactors, loaders, etc. ROPS, FOPS and TOPS are defined in various standards which define the requirements that the structure has to pass. Prototype testing is the only way to pass these standards and often the statement 'If it looks strong and bulky, it must do the job' governs the design.

Finite element (FE) methods are rare in aiding the physical tests. Historically a lot of research has been done on ROPS in the 1970s as a reaction to the number of fatalities in over-turned tractors. Mathematical models developed by Chisholm [1] formed the basis for standards development such as SAE J2194 [2] and OECD Standard Code 4 [3]. Late 1990s and early 2000s saw the use of FE in ROPS validations in many research papers such as [4,5,6] just to list a few. Despite the fact that the FOPS standards have been developed similarly to ROPS standards, there is much less evidence of FOPS FE simulations to validate the standards or develop any mathematical or numerical approach to FOPS. Kaneda and Tamagawa [7] have

analyzed FOPS using the commercial software PAM-CRASH. Their findings have shown good correlations between the measured and calculated values in terms of time-displacement measurements.

There is an increasing demand for light-weighting, reductions in CO₂ emissions and cost saving in the off-highway vehicle sector. This encourages the sector to look for alternatives and the success of aerospace and automotive industries in using the FE technique is becoming an attractive way of improving a design. The trust in Computer Aided Engineering (CAE) in heavy machinery has still a long way to go though. This study is aiming to reinforce this trust.

Two overhead guards (OHG) used on a forklift truck (Figure 1) have been kindly donated by Hyster-Yale Group to R&D of Tata Steel. The FOPS standard [8] for a forklift truck has been used as a basis to develop the two tests - static and dynamic. The static test was developed to ensure that enough data is collected to be able to correlate with FE simulation. The dynamic test was designed to be as close to the real test as possible (given the fact that the standard test is done on the full vehicle) to see how close the FE simulation can get to the test data. A dynamic test is usually difficult to correlate due to the noisiness of the data and short duration of the test. Material testing is essential for this type of study and this was planned in the testing schedule.



Figure 1. HYSTER Forklift Truck

The paper describes the non-standard physical tests, the FE simulations and a comparison of the results. The study is split into four sections. The first section briefly explains the FOPS standard and the motivation behind the development of Tata Steel's own test procedures to do this study. Material testing is explained briefly in the second section, together with its importance for FE analysis and the material data source. The third section touches on the FE method, software versions and few less common LS-DYNA features used during the FE simulations. The fourth and main section then describes in much more detail the tests and FE set-up, results obtained and their comparison with a conclusion in the Summary section.

OHG TEST STANDARD

The chosen 3.5tonne forklift truck undergoes testing given by the standard [8]. The truck is tested in its full assembly (Figure 1) and according to the standard it is subjected to a sequence of the following tests: a non-destructive static test, 10 times 45kg cube drop test and an impact lumber drop test. If applicable, there could also be an angle impact drop test, penetration test and/or the 45kg cube dropped onto the cowl or other structures intended to protect the operator's legs and feet.

The static load test consists of applying a uniformly distributed load on the top of the OHG for at least one minute. The test load depends on the rated capacity of the truck. The test is passed if no part of the OHG or its attachment exceeds 10mm of permanent vertical deformation.

The drop test with a 45kg cube consists of a sequence of 10 drops of the cube strategically located 1525mm above the OHG (locations and their tolerance are given by the standard). After the 10th drop, minor cracks are permissible, but any completely broken parts will fail the test. Permanent deformation after the last drop may not exceed 19mm.

The impact drop test consists of dropping a large lumber load onto the OHG. The weight and height of the load depends on the truck rated capacity. Same as with the previous test, any broken parts would fail the test; however, minor cracks are permissible.

The R&D department of Tata Steel has not followed these standard procedures, but has developed their own. There was couple of reasons for doing so. Firstly, only the frame of the OHG has been available for testing and not the whole forklift truck as is required in the standard test. Secondly, there was a desire to collect as much data from the test as possible, especially from the static test. The standard static test does not deform the OHG significantly; therefore it would have been difficult to pinpoint the exact locations for the strain gauges to measure some data of reasonable values. The frame needed to deform such that plastic deformations were achieved in pre-defined locations.

MATERIAL TESTING

The material used for the OHG was specified as S355J2 (EN10025-2:2004). For a good correlation of the test with FE simulation it was essential to do at least a basic material tensile test. No extra material samples were available so after the two tests the OHGs were cut up to obtain the tensile test samples. The samples were taken from the areas of the OHG where there was no plastic deformation during the two tests, such as the rear of the roof bars and legs (Figure 2).

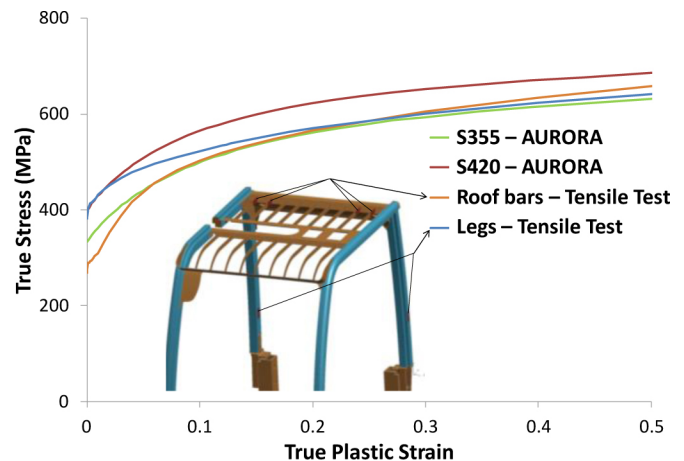


Figure 2. Quasi-static stress-strain curves from tensile tests with the location of samples taken from the OHG.

The legs of the OHG have been subjected to forming strains during manufacture, so it was expected to get higher strength material from the samples taken from the legs. This is exactly what has happened. Figure 2 shows the quasi-static true stress-true plastic strain curves as calculated from measured engineering stress-strain curves obtained from tensile test compared to the curves from the Tata Steel's AURORA material database. It is clear that the tensile test on the roof bars samples matches the S355 database curve to a high degree. Samples taken from the legs have resulted in higher strength curve at the beginning matching the S420 stress-strain data from the AURORA database, but then gradually joining the stress-strain curve of S355 at about 0.2 true plastic strain. This is exactly the behaviour of material hardened by forming.

Usually the quasi-static stress-strain curves are sufficient input for the static tests. However, the dynamic testing requires the strain rate stress-strain curves. Due to the lack of sufficient amount of material from the remaining OHGs and lack of resources, it was not possible to obtain the strain rate stress-strain data by testing. The Tata Steel's

AURORA database has the full range of stress-strain data for both S355 and S420. Using these and the quasi-static stress-strain curves from the tensile testing the two full sets of stress-strain data have been adopted and appropriately adjusted to be used in the present FE simulations in the form as shown in [Figure 3](#).

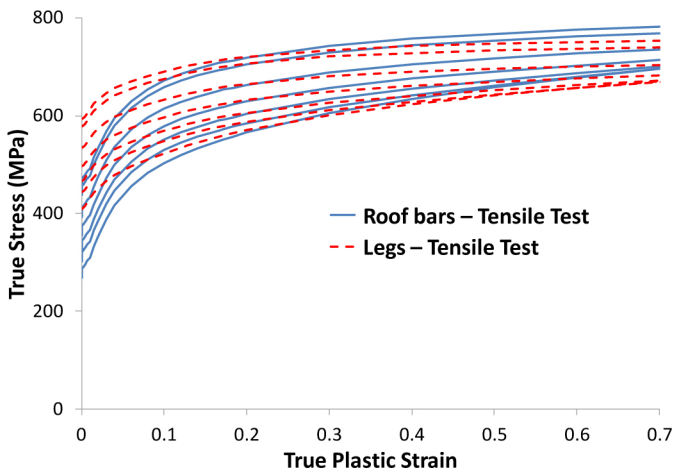


Figure 3. Two sets of strain rate stress-strain curves used in FE simulations.

FE SIMULATIONS SET-UP

The static simulation has used the implicit solution of LS-DYNA [10,11]. The force displacement curve from the test has been adopted for the FE simulation. The test displacement-time curve has been smoothed and applied in FE as displacement boundary conditions imposed on the rigid loading block. In the test, the OHG has been pre-loaded up to 10kN to check that all the instrumentation was working. The load has been released and all instrumentation reset to 0 before the start of the static test. This pre-loading of the OHG has also been modeled in the FE simulation.

In the test, the max load has been held for about 10 minutes, while all FaroArm measurements have been taken. The FE simulation has omitted this time; the loading curve was reversed straight after the max load had been reached and slowly downloaded to complete the release of the load on the OHG.

Element formulation of type 2 - Belytschko-Tsay shell elements with 5 through thickness integration points modeled the frame.

Approximate size of the shells was 8-12mm to create a reasonably sized model which would not take too long to run and therefore could be used as a guide in development stage of a design. It was felt that the mesh sensitivity study was not needed since the work preceding this correlation study on the same frame has proven to give satisfactory results.

The '*MAT_PIECEWISE_LINEAR_PLASTICITY' card with its option for tabulated data has been used for both static and dynamic simulations.

Modeling of welds has not been considered - the joints were created by careful alignment of the mesh. This simplified the requirements for contact modeling by omitting the self contact of the structure and any possible weld/joint contacts often used in automotive crash event

modeling. The only contact needed was therefore the automatic nodes to surface contact between the loading block bottom surface and the frame nodes with friction coefficient 0.1.

The dynamic analysis has used a combination of explicit and implicit solutions. The explicit solution had modeled the impact event while the implicit solution has been used to 'calm down' the vibrations of the structure after the impact. The last state of the deformed shape, including the stresses and strains has been saved in a 'dynain' file after each drop using the '*INTERFACE_SPRINGBACK_LSDYNA' card. This file was then used for the subsequent next drop simulation as an input file. This way the deformations and strains from all ten drops were accounted for when looking at the final deformation of the OHG.

Before the release of LS-DYNA Version 971 R7.1.1, the 10 drops had to be submitted separately meaning that each individual simulation of a drop had to finish creating the dynain file as the input before the next drop could be manually submitted. After the release of LS-DYNA Version 971 R7.1.1, the '*CASE_option' card had simplified the process of submitting all 10 drops in only one input file.

THE PHYSICAL TESTS SET-UP AND ITS REPRESENTATION IN FE MODEL

Both OHGs (one for the static test and one for the dynamic test) were bolted and welded to the strong floor. Most of the instrumentation attached to the OHGs has been used in both tests. The following gives the detail description of all the instrumentation and how it was related to the FE modeling.

Static Test

Wire Transducers Measurements

For the static test only, a frame has been fixed around the OHG. Seven wire transducers were then attached to this frame and the OHG to measure the continuous displacements of the OHG's roof. [Figure 4](#) shows the locations of the wire transducers in the test and the nodal IDs of the corresponding positions in the FE model. The measurements in both test and FE simulations provided the force displacement curves for comparison.

Force-displacement curves are usually the first indications of a good correlation result. [Figure 5](#) shows the comparison of the force-displacement curves as measured in test by the wire transducers and FE curves obtained from the displacement of the corresponding nodes. For example WT03 and FE node ID 11040 ([Figure 4](#)) had the same location on the OHG in test and FE model, respectively.

The solid lines in [Figure 5](#) are the force-displacement curves from FE and the dashed lines are from the test. The vertical displacements measured in the Y-direction reflect the directionality of the displacement. Some of the points have moved upwards. For example the curves for point WT08 in test and node ID 4842 in FE simulation are at the negative side of vertical displacements in [Figure 5](#). This point represents one of the free ends of the crane arm, the second free end - WT15 the side rail for the battery crane hoist.