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STRUCTURAL-MECHANICS ANALYSIS OF THE 10G TRANSFORMER IMPACT

SUMMARY

Transportation of the power transformers from the site of production to the site of the exploitation is very complex and sensible task. During transportation, the transformer can be subjected to a variety of different impacts registered either during railway transportation or during on/off loading. The transformer should be designed to sustain the high accelerations appearing often during transportation.

Transformer are usually equipped with the impact recorder to registry the acceleration behavior during the transport. In the current paper, we give an overview on the structural-mechanics analysis of 10g impact on the power transformer registered during the railway transportation of the transformer from Canada to US.

1. INTRODUCTION

The main task of this study is to analyze the consequences of the mechanical impact appearing during the transportation of the single-phase transformer from ABB Varennes Factory to the customer site. The transformer was a single-phase auto transformer with rating of 746√3 to 345√3 kV, 450/600/750 MVA and with tertiary rating of 34.5kV,60/80/100 MVA. Two identical units were shipped at the same time. Impact events were recorded on the two impact recorders that were installed on one of those units.
As the power transformer has failed in operation at its installation site afterwards, the cause of failure had to be investigated. For this purpose, numerical simulations are done. These simulations should support the clarification whether the impacts during transport are cause for the malfunction:

- A detailed finite element model is established to analyze the dynamic behavior of the transformer and to assess stress and displacement of the structural members.
- The general dynamic behavior is represented by the natural frequencies and the related mode shapes of the structure. These are the results of the free vibration analysis.

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- The effects of the impact loading are calculated with RSMA (Response Spectrum Modal Analysis) method. The static load case *dead load*[1] is regarded.
- Displacements and von Misses-stresses[2] are calculated responses.

2 Transformer model

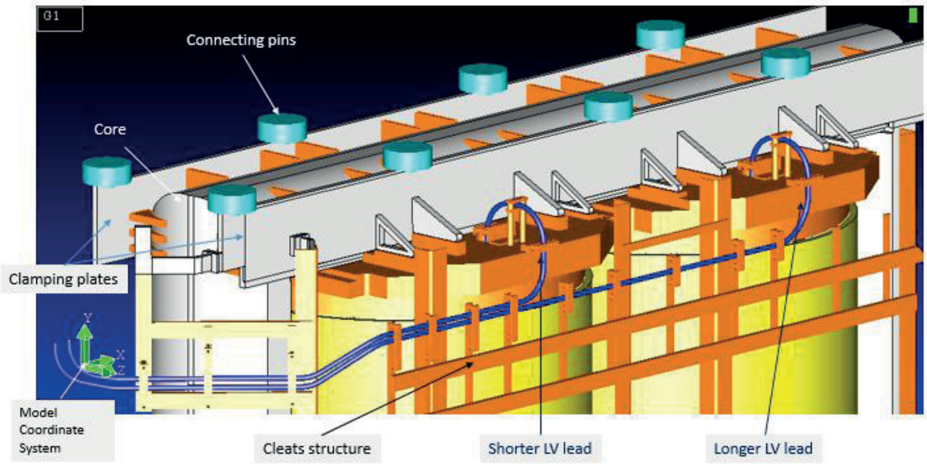

Figure 1: Transformer model

3 Mechanical Analysis Methodology

As loading conditions, the *dead load* (DL) and *impact* are specified.

3.1 Operation Loads

The response of the transformer due to *dead load* (gravity) is calculated in a ‘static load’ step.

3.2 Impact Loading

During the transport of the transformer an excessive impact was sensed. This impact was measured by two shock recorders mounted on the top of the tank at the manhole, Figure 2.

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[1] *Dead load* is synonym for the *gravity load* defined by the weight of the structure itself.

[2] *Von Misses stress* is a mechanical quantity used to check if the material will withstand a given load condition

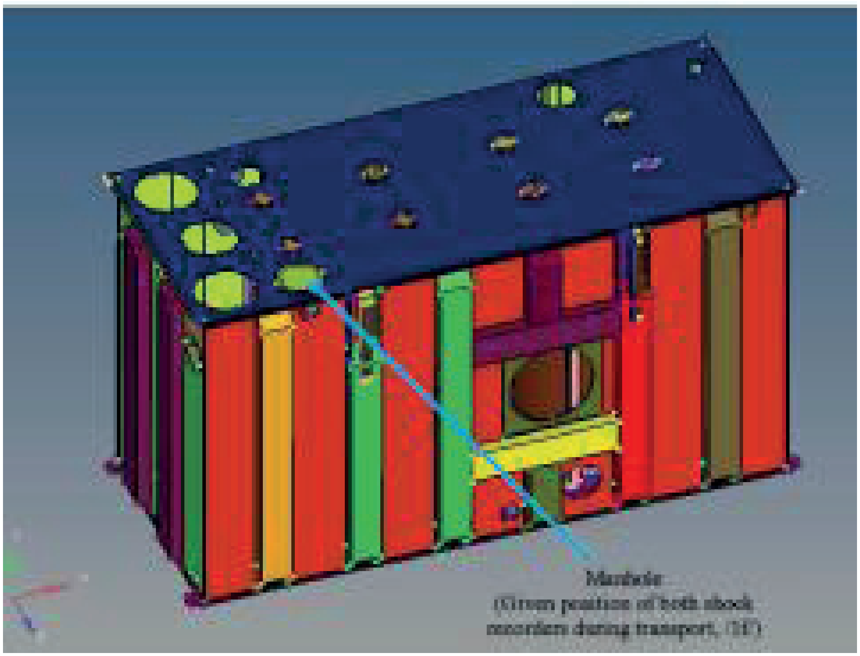

Figure 2: Position on the tank top where the recording devices were mounted

As the real impact happened at the bottom of the transformer tank, the measured information at the top of the tank was in fact the response of the real impact happening at the tank bottom. To obtain the loading at the tank bottom it was necessary to evaluate the *inverse response function* based on the measured signal[3]. For the impact loading the enveloped response spectra for a damping value of D = 2 % are applied. As there is no information given on the structural damping of the transformer, this value is applied as a conservative approach. The enveloped response spectra are used to calculate the structural responses of the transformer due to impact in x-, y- and z-direction[4] induced at the boundaries of the FE-Model by RSMA (Response Spectrum Modal Analysis).

The recorded time histories of both recorders are transferred into *response spectra* showing the impact signal in the *frequency domain*, Figure 3. The dominant component of the impact recorded on both recorders was the *vertical* one, but two other components were also present.

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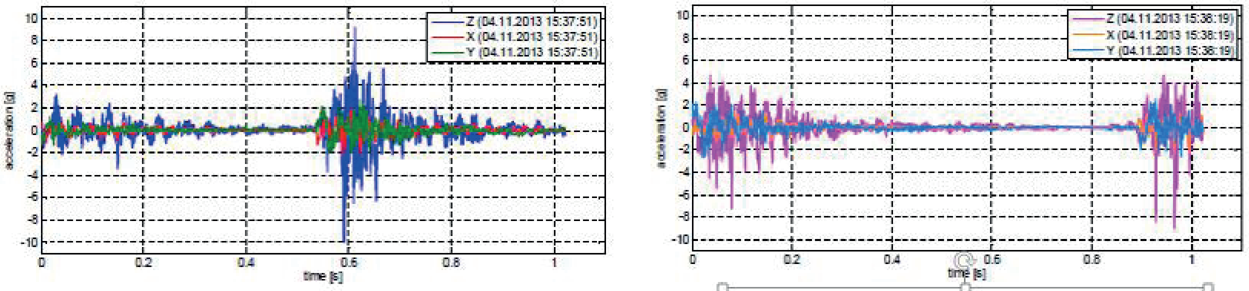
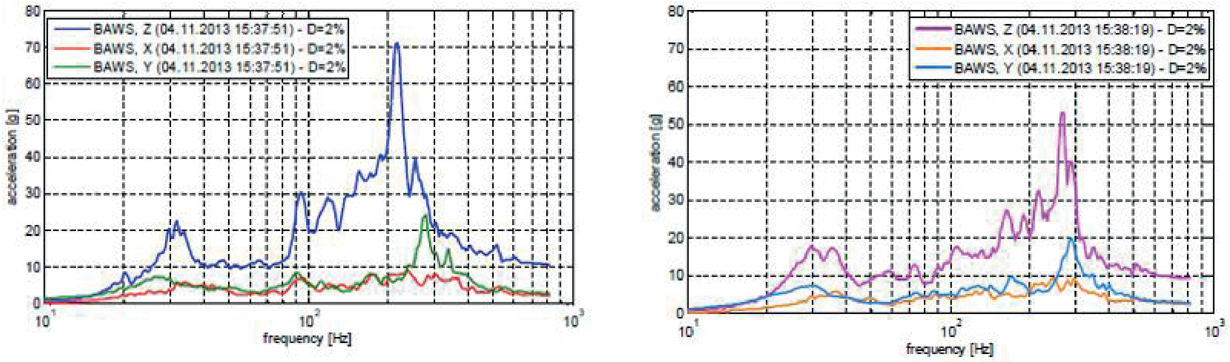
[3] Nevertheless, the recorded signals were regarded as loading at the bottom.

[4] Note: The coordinate system of the measured signal and of the simulation model differ! Vertical component in the measured signal is in "Z"-direction, whereby the vertical component in the model is in "Y"-direction.



a.) Recorder 1: Measured impact signal in time domain

b.) Recorder 2: Measured impact signal in time domain



c.) Recorder 1: Calculated response in frequency domain

d.) Recorder 2: Calculated response in frequency domain

Figure 3: Impact signal in time domain (recorded) and in frequency domain (calculated as a point mass) for both recorders

The response spectrum (or shock response spectrum) shows the peak vibration response (e.g. acceleration) of a single degree of freedom system (oscillator made from a mass put on a spring and damper) due to an arbitrary transient acceleration input (e.g. shock) at its base. The abscissa gives the natural frequencies of the oscillator; the ordinate gives the corresponding peak response for a defined modal damping value.

4 RESULTS

The analysis is carried out with the software ABAQUS[5]. In Free Vibrations the results of the free vibration analysis are documented. Displacements and stresses according to *dead load* as well as displacements and stresses according to load combination *dead load* with *impact* respectively are documented in Response to Dead Load and Response to Impact Loading and to Impact Loading with dead load, respectively.

4.1 Free Vibrations

With the FE- model described above the modal parameters are calculated up to a frequency of 350 Hz. The distinctive mode shapes (up to 30 Hz) with high modal masses are shown in Figure 4. It illustrates the trends how the transformer structure moves for different frequent modes (blue lines show the initial position).

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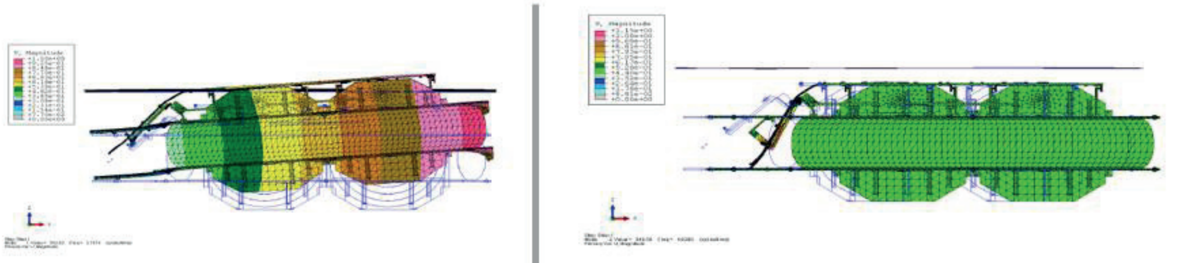
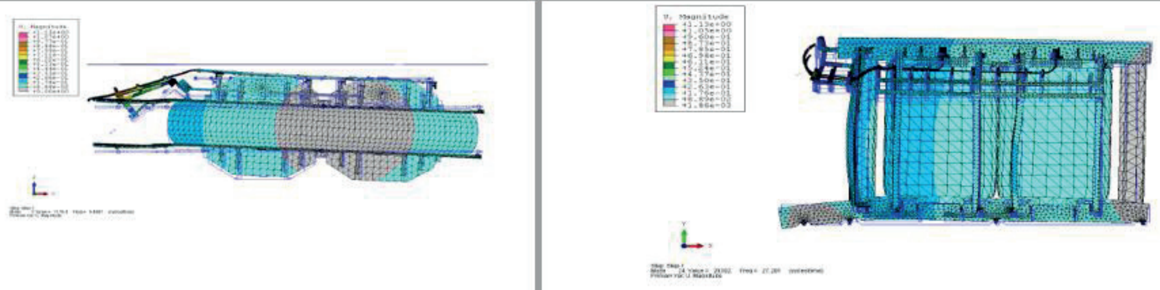
[5] Abaqus Unified FEA, Version 13.2; Dassault Systèmes



a.) Displacement (trends) for mode 1 (f=3.7 circles/time)

b.) Displacement (trends) for mode 2 (f=4.63 circles/time)



c.) Displacement (trends) for mode 3 (f=5.45 circles/time)

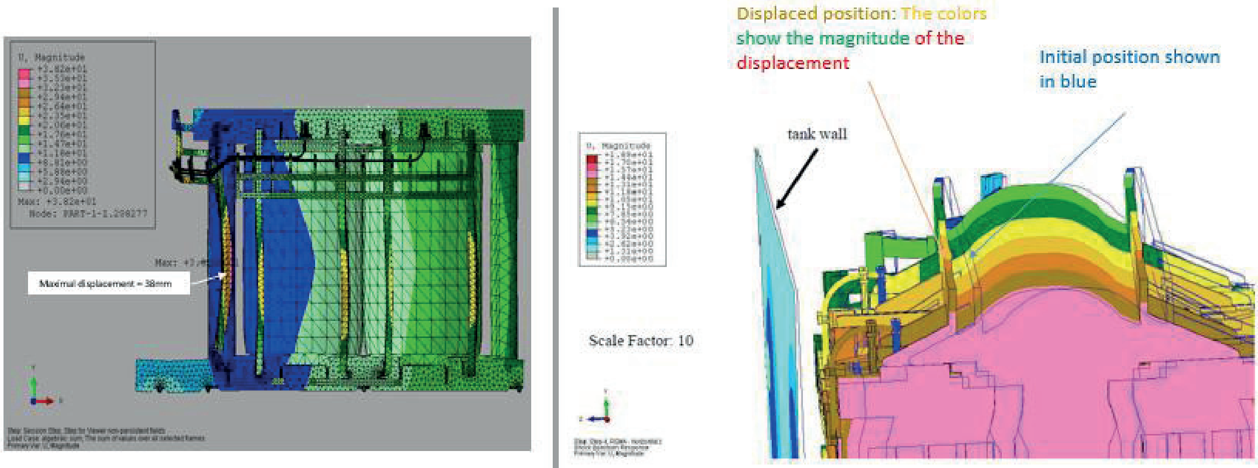
d.) Displacement (trends) for mode 24 (f=27.28 circles/time)

Figure 4: Distinctive Eigenmodes

The Eigen-frequencies up to 350 Hz are calculated; the contributions of higher Eigenmodes are considered insignificant as the modal effective mass of the considered modes is > 95 %.

4.2 Response to Impact Loading and to Impact Loading with dead load

The results due to impact loading in X-, Y- and Z-direction as well as their SRSS-combinations are regarded. The stress results are discussed for the different materials separately.
The maximum displacement (algebraic-combination of impacts) in the whole transformer is approx. 38 mm and appears at the cleat structure (see Figure 5, a) which is approx. 4000 mm long.



a.) Displacement of the whole structure. Max. displacement is on the cleats structure 38mm.

b.) Displacement of the upper part of the transformer structure.

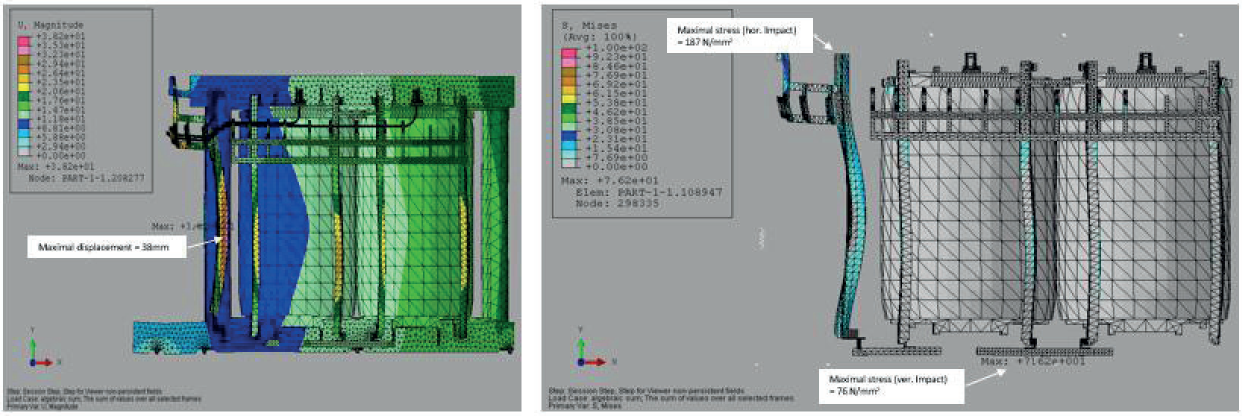
Figure 5: Displacement of the whole transformer structure

Figure 5, b gives a closer view to the displacement of the upper part of the whole structure. Initial positions are shown in blue. Different colors represent different displacements.

4.3 Pressboard structure

4.3.1 Pressboard Cleats Structure

Maximal displacement appearing on the cleats structure is in range of 38 mm.

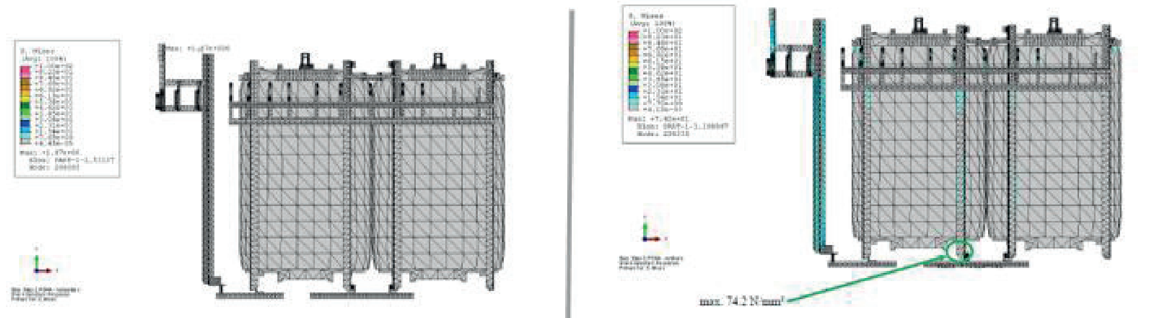


a.) Maximal displacement of the pressboard cleats structure is 38 mm

b.) Maximal stress of the pressboard cleats structure is 187 N/mm^2 (horizontal impact) and 76 N/mm^2 (vertical impact)

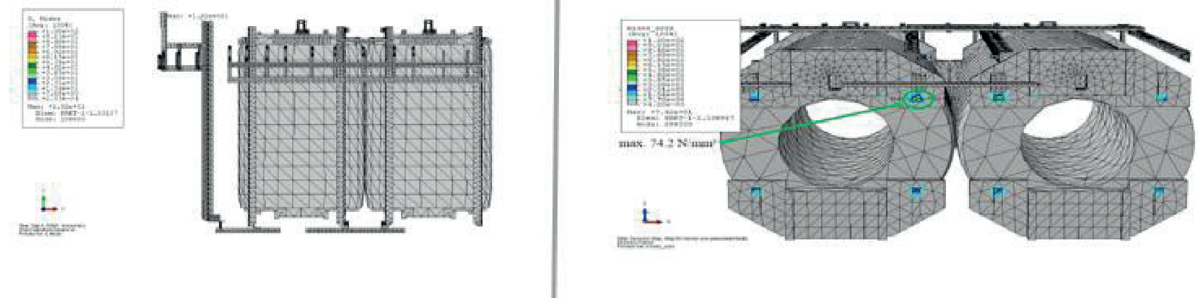
Figure 6: a.) Maximal displacement of the cleats = 38mm; b.) Maximal stress appearing on the cleats is around 187 N/mm2 (horizontal impact) and 76 N/mm^2 (vertical impact).

Maximal stress of the pressboard cleats structures is around 187 N/mm^2 for horizontal impact and 76 N/mm^2 for vertical impact, Figure 7. As the allowable yield stress for the pressboard is in the range 60-200 N/mm^2, at certain positions the calculated stress is above the minimal yield stress. It is also known, that for some types of the material (pressboard is one of those) it can cause breaking of the structure, even without achieving the “plastic” stage.



a.) Von Misses stress on the pressboard structures due to horizontal impact in X-direction (max. = 187 N/mm^2)

b.) Von Misses stress on the pressboard structures due to vertical impact (max. = 74.2 N/mm2). Yield stress for pressboard varies from 60 – 200



c.) Von Misses stress on the pressboard structures due to horizontal impact in Z-direction (max. = 10.1 N/mm^2)

d.) Von Misses stress (calculated as SRSS) in the pressboard bottom parts (max. 74.2 N/mm^2)

Figure 7: Stresses due to impact on pressboard structures

4.4 LV Leads

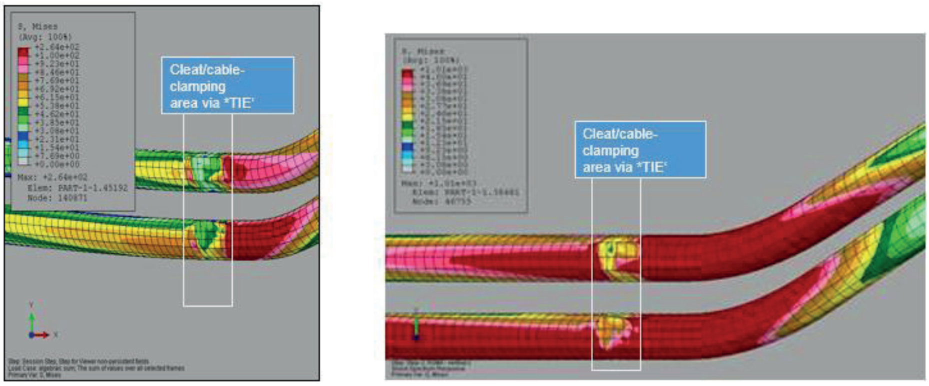
The impact accelerations had a significant influence on the mechanical behavior of the LV leads. Two LV leads (“shorter” and “longer” design layout shown in Figure 1) are located at the HV side (front side) of the transformer. These leads are, with the help of the cleats structure, lead out of the tank.

4.4.1 Stresses on LV Leads

Assumptions

In the current analysis, we have assumed that the yield stress for Cu is laying between the 40 and 100 N/mm^2. In the real design, the LV leads are the bundled cables made of a number of the Cu wires, wrapped by the paper insulation. In the analyzed model, we assume the solid Cu structure for the LV leads. More precise information on the yield stresses of the bundled cable structure were not available during analysis.

From the detailed view on the cables bending positions shown in Figure 8, especially when considering the lower limit of 40 N/mm^2, the most overstressed position is near the cleats-keeping parts.

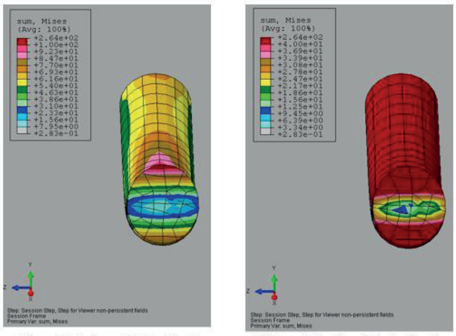


a.) Stress distribution on the LV cable for the upper yield stress limit of 100 N/mm^2.

b.) Stress distribution on the LV cable for the upper yield stress limit of 40 N/mm^2

Figure 8: Stress distribution on the bending positions close to cleats

In Figure 9 it can be seen the stress distribution inside of the cable for a.) *Yield* limit of 100 N/mm^2 and b.) *Yield* limit of 40 N/mm^2 can be seen.



a.) Stress distribution within the LV cable for the upper yield stress limit of 100 N/mm^2.

b.) Stress distribution within the LV cable for the upper yield stress limit of 40 N/mm^2

Figure 9: Stress distribution within the Cu cables

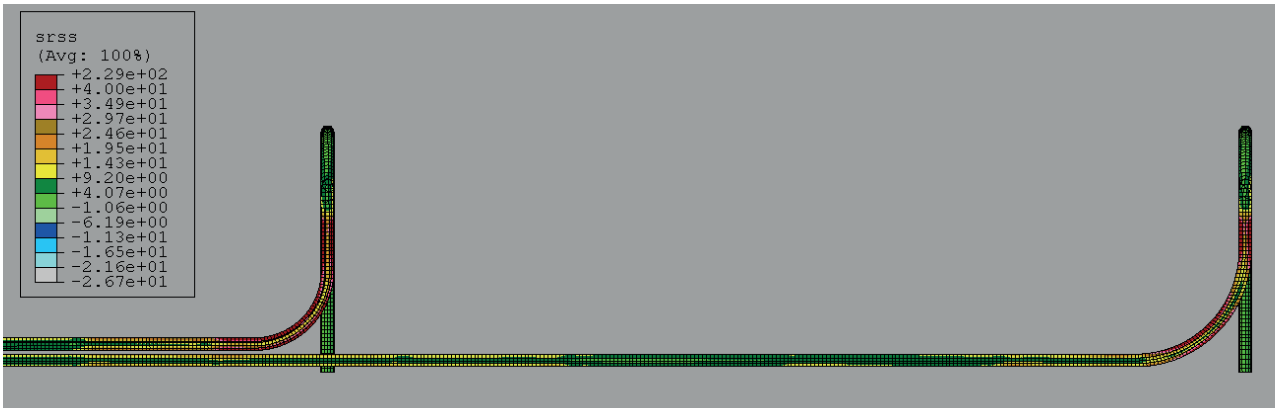
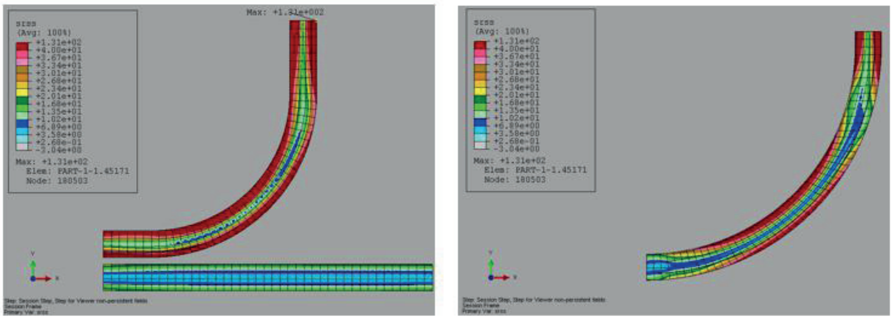


Figure 10: Comparison of the stresses on the shorter and longer LV lead (combination of impact by SRSS method)

Figure 10 shows the stress distribution on the shorter and longer lead. It is visible that the short cable has higher stresses at the bending positions than the longer cable.

Figure 11 shows the stress distribution over the cut of the conductors on the bending position in front of the limbs: a.) Shorter cable and b.) Longer cable.



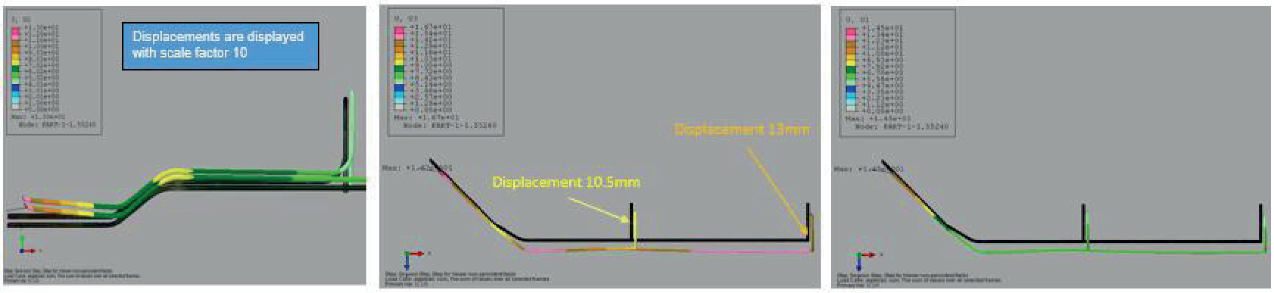
a.) Shorter cable

b.) Longer cable

Figure 11: Stress (SRSS combination) at the bending positions of a.) Shorter cable and b.) Longer cable. Colors scaled for the lower limit of yield stress 40N/mm^2

4.4.2 Displacement of the LV Leads

All three components of the impact acceleration cause the displacement the whole structure, including the displacement of the LV leads. Figure 12 show the displacement of the LV cables in both vertical and two horizontal directions (towards and along the tank wall).



a.) Vertical displacement. Initial position shown in black.

b.) Horizontal displacement in Y-direction (model COS) towards the tank wall. *Initial position shown in black.*

c.) Horizontal displacement in X-direction (model COS) along the tank wall. *Initial position shown in black.*

Figure 12: Displacements of the LV leads structures: a.) vertical displacement; b.) horizontal Y-displacement; c.) horizontal X-displacement

The total horizontal displacement of LV lead at the bending positions in front of the limbs is in the range of 10.5 mm (for shorter cable) to 13 mm (for longer cable), Figure 12, b.

4.5 Steel Structure

Figure 13 show the von Misses-stresses caused by the impact signals in X-, Y-, and Z-direction. The critical stresses for steel are not given, but a yield stress of 300-500 N/mm² is assumed. At the bottom connectors and bottom clamps the high values of von Misses stresses (SRSS-combination of impacts has a maximal value of 14.600 N/mm^2) significantly exceed the yield stress of 300-500 N/mm²in the wide area. Material plasticity and permanent deformations in these areas are very likely.

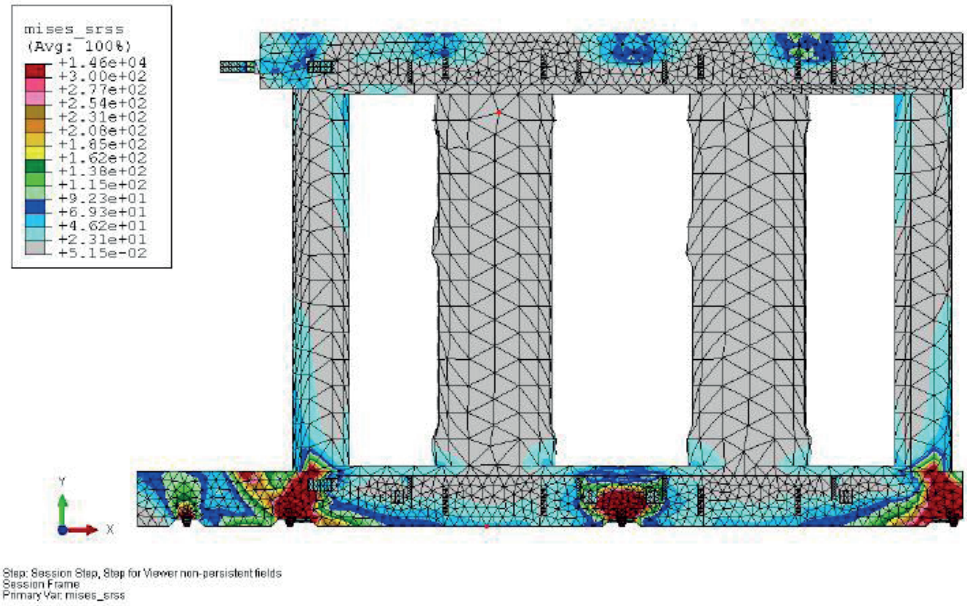


Figure 13: Very high stresses appear at the connecting pins positions. Local maximal value 1.46e^4 N/mm^2 is much higher than the standard yield stress value for the steel (300-500 N/mm^2).

5 CONCLUSION

The responses (stresses, displacements) of the transformer due to *dead load* and *impact* were analyzed using a linear FE-model as well as linear calculation methods. The goal was to determine whether local plastification / deformation of the structure can be expected due to the experienced impact loading during transportation thus clarifying whether the impacts during transport are potential cause for the malfunction.

The *dead load* loading was evaluated by a static analysis using -1 g vertical loading. The results show a maximum total displacement of 0.4 mm. The von Misses-stress levels in the structure are very low except areas in the clamp plates where the transformer is supported by the eight bottom connectors. In the connector regions, von Misses-stresses of approx. 213 N/mm² are reached (not shown above). This level is quite high regarding the fact, that only dead load is considered. With an assumed average yield value for steel, a usage of 71% (213/300) is already reached for Dead load.
An analysis of the Eigen-behavior of the transformer shows that the basic global horizontal modes are below 5 Hz (see Free Vibrations), in vertical direction the global motion is associated with Eigen-frequencies in the range 27.2 to 29.2 Hz. Above these frequencies the effect of the impact has (with increasing frequency) less and less effect when stressing of the copper cables or cleats is regarded. Above these frequencies the transformer is „base isolated “. This effect can be seen from the transfer functions (from the base to the transformer top in each direction, not shown).

The responses due to *impact* were analyzed by response spectrum modal analysis (RSMA). For this purpose, the recorded acceleration time histories of the two shock recorders were transferred to response spectra using a modal damping value of D = 2 %. Enveloped spectra were afterwards used to calculate the maximum responses of the transformer due to shock loading in X-, Y- and Z-direction. The responses of these three shock loadings were combined and added to the results of the *dead load* loadcase. These final results (*dead load* + *impacts*) show that:

- Von Misses-stresses in the pressboard are partially approaching the yield limit,
- Depending on the yield stress value of the copper, material plastification and local displacements are more or less likely,

- At the bottom connectors and bottom clamps of the steel structure local material plasticity, which could result in permanent displacement of the entire transformer, is likely.

6 Appendix: Index of Abbreviations

Abbreviation	Meaning
CAD	Computer-Aided Design
COS	Coordinate System
CQC	Complete Quadratic Combination
DL	Dead Load or Gravity Load
FE	Finite Elements
RSMA	Response Spectrum Modal Analysis
SRSS	Square Root of Sum of Squares
Von Misses Stress	Used to check whether the material will withstand a given load condition