

Drop test validation of a virtual prototype of EV Battery Pack

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Abstract. This study explores the validation process of a drop test virtual FEM experiment of a complex structure - battery pack. A physical prototype has been manufactured and subjected to drop tests, where its impact behavior has been examined through the use of high-speed imaging and visual tracking software. Different indicators have been used in order to validate the virtual analysis through adjusting materials, boundary conditions and analysis settings. A validated virtual analysis gives an insight of the deformations and stresses in different areas of the tested assembly that can be used for further geometry optimization and/or certification.

INTRODUCTION

In the search for more sustainable transport methods, many alternatives are on the rise. Electric and hydrogen vehicles of different categories are being supported by governments and sought after by consumers [1], hence more innovations into energy efficiency and safety are being implemented, leading to a rise in electric vehicle production [2]. This is a prerequisite for meticulous testing for standalone components and complete systems which is mandatory in order for mass production to start. Batteries are the most critical item onboard the electric vehicle as they present several potential hazards, including electrical, mechanical, chemical and explosion hazard. [3] Different test procedures including impact tests, environmental influences and vibration tests are introduced on the prototype level in order to ensure proper functionality and user safety. Furthermore, a valuable approach in order to ensure compliance with the said tests and to predict the subject's behavior is virtual prototyping and finite element analysis (FEA). According to the white-black box model [4], where experiments are accurate but simulation offers a greater insight of the object's behavior, alterations can be introduced without a considerable increase in the cost in the prototyping phase. [5] Plastic and elastic deformation, material stress during mechanical tests can be extracted, based on which endangered sections and critical regions can be monitored and revised. Through physical testing the virtual model can be validated, using different criteria such as rebound velocity, contact time, elastic and plastic deformation, etc. [6] After validation, initial conditions for which it is more complex to conduct physical testing can be virtually executed, thus extracting valuable information without the added financial and time resource of manufacturing and destroying prototypes, evaluating early the associated risks in an impact scenario.

This study follows the said approach and through the physical validation of a simplified EV (Electrical Vehicle) battery pack assembly for a drop test scenario, a validated virtual model is extracted and used for further analysis. The tested base pack is the smallest assembly according to the eggshell concept, which in this case consists of battery cells, which are assembled in base pack, which on their own are assembled in a subpack, which are integrated in different types of vehicle chassis. As such mechanical influence could occur during battery assembly and disassembly and potentially pose danger to the operational staff and manufacturing site. ISO 16750-3 is the applicable standard and concerns all subunits in the battery pack. It targets to avoid failures (e.g., a loose electrical connections inside the

housing of an electronic control module due to the high accelerations when the device hits the ground, which could lead to fire hazard) that could not be detected visibly and the battery pack could be installed in the car. This study expands those requirements even more, covering more LCs (Load Cases) - the required by standard three, plus two additional unfavorable ones, as are shown in Table 1 below. An isometric view of the test body and the respective axes for easier representation is shown on Table one, as X Y and Z are defined as the model's coordinate system, whereas X4, Y4, Z4 is the coordinate system intended for LC4 on which the focus of this paper lies on. Both coordinate systems have the same origin, as on Table 1 the LC4 coordinate system is placed in the lower right corner for clarity. Thus, to reach the LC4 coordinate system only a rotation around the Z axis from the XYZ is introduced by applying the following coordinate transformation:

$$\mathbf{p}_{LC4} = R_z(130^\circ) \mathbf{p}_{Detail}$$

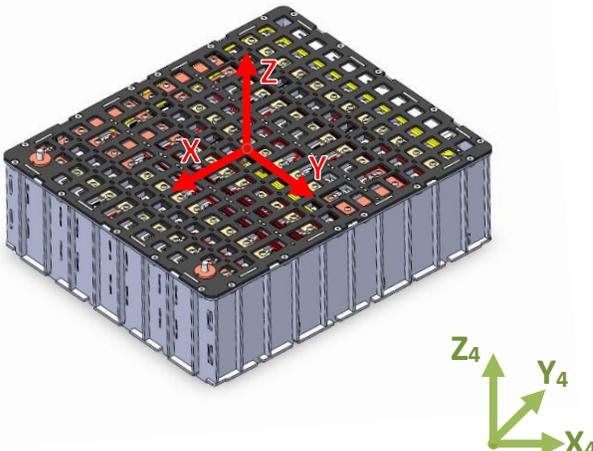
where

$$R_z(130^\circ) = \begin{bmatrix} \cos 130^\circ & -\sin 130^\circ & 0 \\ \sin 130^\circ & \cos 130^\circ & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The first three load cases inspect the influence of the drop test on the three different faces, while the additional two look into edge and tip contact. This way the component integrity and functionality can be assessed even with visible signs of damage in order to ensure safety during manufacturing and assembly. Nonetheless, in this paper only figures from one load case experiments and simulation are presented and results are summarized due to the large volume of data. LC4 is selected due to the good visual representation of test and simulation results. In summary, the main goal of the study is to predict if any hazard would occur in the case of a 1 meter drop of an EV battery pack, thus evaluating the proposed structure and geometry, while the product is on the prototype level, while still some alterations can be introduced in the design geometry.

TABLE 1. Examined load cases

Load Case #	Direction of free falling
1	Z axis
2	Y axis
3	X axis
4	XY combined (Y ₄ axis)
5	XYZ combined



STUDY METHODOLOGY

A methodology for impact testing of a newly developed product has been presented. It is composed of three main parts, involving preparation and conduction of physical prototype experiments, simplified virtual model preparation and validation, virtual model calibration and final virtual model computation. The goal is to obtain detailed results for mechanical influences that are not possible to reach through conventional physical experiments.

This specific study follows the presented methodology, aiming to find out if the observed device in its manufacturing state could pose a hazard in the consequence of a mechanical influence – drop test and would pass required tests, before starting mass production. For this approach, five separate load cases have been prepared for the experimental setup, however due to mass fracture and broken shards in LC3 and LC5, they are excluded in the validation stage and the other 3 LCs are approved for validation and prepared as virtual models. Initial conditions for those load cases in the virtual and physical environment are similar, allowing for a direct comparison of results to form robust conclusions. After validation of the simplified VP (Virtual Prototype), final computational model is prepared and tested. Conclusions regarding the subpack behavior and safety are derived from the results of the final analysis.

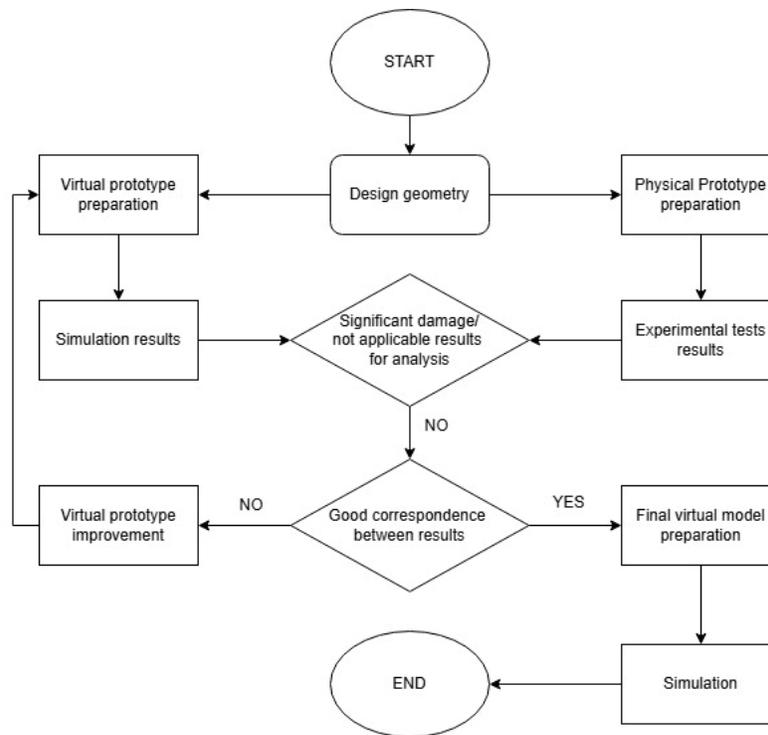


FIGURE 1. Study methodology diagram

The validation process is conducted through physical and virtual experiments of a simplified unit, filled with empty dummy cells, due to the hazards associated with mechanical testing of high-power electrical devices. Additionally, the significantly higher weight would lead to bigger plastic deformation and mass breakage, which would create difficulties for the validation phase. On the other hand, a simplified and lighter construction creating smaller impact forces, allows for a more precise analysis of the plastic and elastic strain of the unit. The simplified unit is subjected to drop tests, captured with high speed imaging for detailed analysis and virtual analyses of different load cases are conducted and adjusted in order to have good results correspondence. After the model calibration the unmodified geometry is tested in the virtual environment. This approach also allows for the use of one prototype for the experimental testing, an approach widely used in the automotive industry.

SIMPLIFIED VIRTUAL PROTOTYPE AND SIMULATIONS

A CAD model of the EV battery pack has been developed outside the scope of this study, and is shown in Figure 2. The design is based on considerations of the internals of the base pack module (battery cells, control unit and wiring), external interface with other modules, thermal behavior, manufacturability and recyclability. After prototyping and approval of the design concept, this design geometry is used as an input for the virtual prototype in the context of this study. As mentioned, the design geometry is simplified for the validation phase, removing electrical connections and components, and replacing full weight battery cells with empty dummy ones, Figure 2c. The cases of the dummy cells have the same load carrying capacity as they are composed only of the battery case, but have a much smaller weight, which as mentioned before is beneficial for the virtual prototype validation. Other electrical components are removed in order for less elements in the discretization field in the context that they do not bring any rigidity to the construction, except for copper battery connections which are subject to plastic deformation during testing and would lead to a more complex model without any considerable benefit. It must be noted that all removed components are once again added to the final virtual model after validation in order to evaluate the complete system behavior.

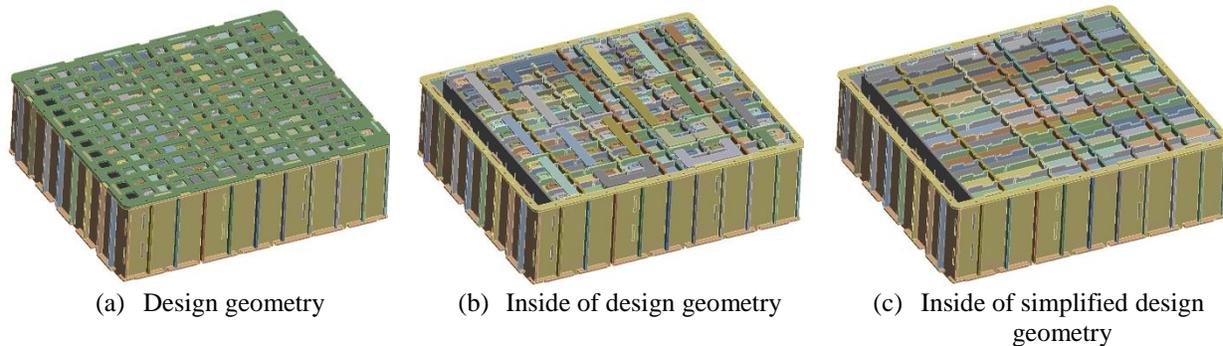


FIGURE 2. Virtual model

An explicit dynamics system has been configured with some specifics which are going to be mentioned in this chapter. Starting with material properties, after some iterations with simplified material definition and only elasticity configured it has been determined that precise material properties and plasticity are substantial for this analysis. Physical tensile testing of 3 identical specimens (outside the scope of this study) of the manufacturing material of the base pack – BayBlend® FR3040 EV (PC + ABS blend) has been conducted. Based on the obtained results, a stress strain curve has been determined, as shown in Figure 3. Furthermore, confirming the validity of the results, the measured yield stress value has a deviation of 3MPa (less than 5%) from the spec sheet of the material. For BayBlend FR3040 a yield strength of 65MPa and Stress at Break of 50MPa is given by the manufacturer. [7] It is to be mentioned that the tensile stress tests are crucial, despite the easily accessible table values for the material, in order to assess the material's behavior through the whole region of its stress-strain curve. Then, this graph is used for defining the material properties in the solver through a bilinear kinematic hardening model, as in the case of the 1m drop plasticity is expected. Other components in the assembly do not exceed their corresponding material yield strength, therefore introducing plasticity for them would not be beneficial.

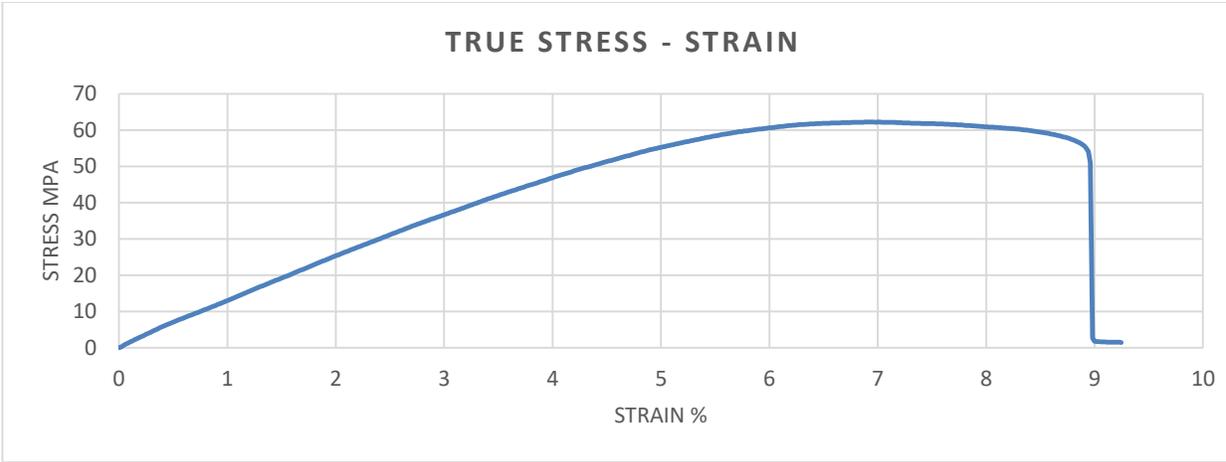


FIGURE 3. BayBlend® FR3040 obtained stress – strain curve

Contacts definition is essential for the accurate representation of the virtual model, due to the relative movement of the battery cells during impact. Simple linear contacts between the battery cells and the housing would increase stiffness resulting in larger accelerations, higher stresses and higher rebound height, or would introduce model instabilities, therefore for this analysis nonlinear contacts should be used. Frictional contacts have been defined with a static frictional coefficient of 0.4 and dynamic frictional coefficient of 0.3 – values in the upper boundary for the materials due to the rougher surfaces of the plastic edges in the physical prototype produced by laser cutting. Linear bonded contact definition has been used for the plastic-plastic connections, despite that through the used RP technologies such bonded contact is not accomplishable, however for the virtual model it is the most accurate option, as only injection molding would introduce this level of adhesion. Due to the contact assumption, some delamination and sliding could be expected in the physical model, leading to a stiffer virtual model, points that are taken into consideration for the validation phase.

Another important point is discretization of the volumes in the virtual model. Depending on the contact orientation, different regions of the assembly ought to have different density of the mesh. Those critical regions with high gradients of stresses are determined iteratively. Spheres of influence of 30mm have been used in the critical regions, transition ratio 0.5 and a growth rate of 2 have been set, ensuring adequate mesh quality in volumes and transition regions. The resulting mesh varies between $2.6 \cdot 10^5$ and $2.9 \cdot 10^5$ nodes and $1.4 \cdot 10^5$ and $1.6 \cdot 10^5$ elements for the different load cases.

Analysis settings for all load cases are set accordingly, with initial velocity of 4.429m/s, corresponding to 1m height drop. In the results and for the model validation LC4 is presented due to its most unfavorable orientation, other load cases have lower stresses and plastic deformation as expected. Additionally, in Figure 4 the X4 and Y4 axes for LC4 have been shown in another view for clarity, besides being presented in Table 1.

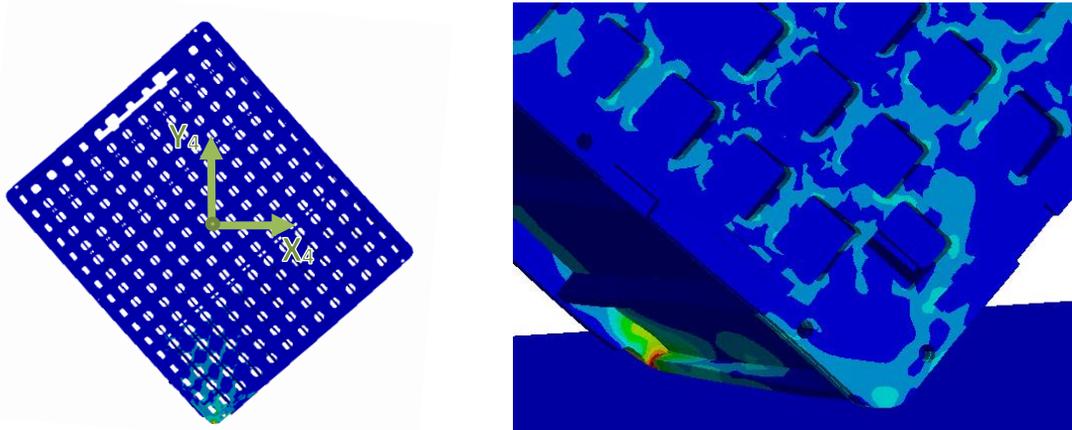


FIGURE 4. Virtual model stress distribution

After computation, the resulting stress magnitude in the case is 153Mpa, with a plastic strain of 0.4%. The cells experience a maximum of 3MPa of stress, respectively no plastic strain. A critical section in the contacting corner has been identified, meaning that a fracture is expected to occur in that region.

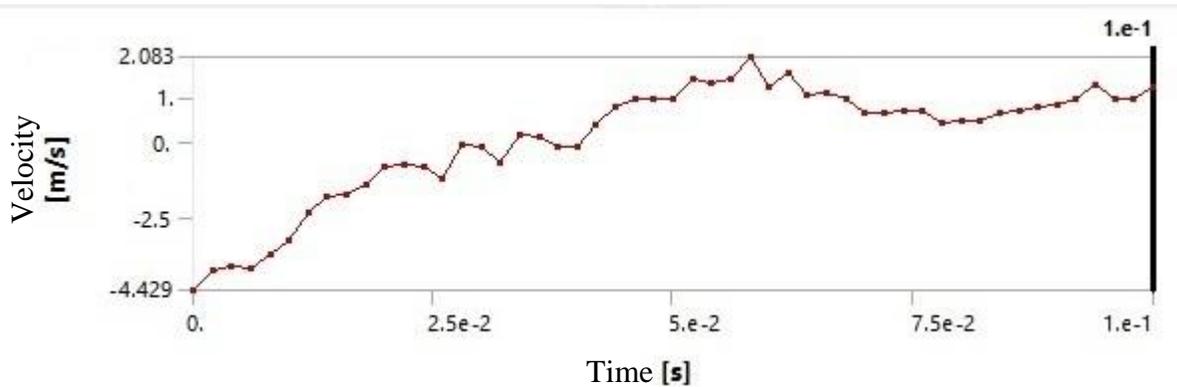


FIGURE 5. Virtual model vertical velocity profile for LC4 for the impact moment

From Figure 5 the velocity profile in the Y4 direction of one of the points that are being tracked and in the validation phase, compared with experimental data for LC4 has been shown. The initial and velocity after impact are shown, and a contact time of around 0.1s is observed, as in this section of the graph the initial contact is shown, after which the speed starts to drop. It is important to mention that for the virtual analysis runs only 0.3 seconds after the contact, because further computations would be unnecessary as the body continues to move with constant deceleration motion. This time frame is determined iteratively in order to be certain that the tested body enters the mentioned motion. According to these criteria the model works as expected in the iteration shown in Figure 4, presenting its comparison with the physical prototype in the validation chapter.

PHISYCAL PROTOTYPE AND EXPERIMENTAL TESTS

The physical prototype, shown in Figure 6 is based on the design geometry and is produced by the technologies of rapid prototyping, in this case laser cutting and chemical bonding. This approach is used because in the process of developing a product, design modifications are often needed and through the RP approach they can be easily introduced without alterations to expensive manufacturing equipment. This however has also its downsides, because the produced construction has different mechanical properties than an injected molded unit, despite using interference fit where possible, and would lead to worse results in some of the mechanical tests. Using a simplified and lighter construction allows for this influence to be minimized as previously mentioned. The specific design considerations and manufacturing by RP technologies lie outside the scope of this study and accordingly only relevant points are presented.



FIGURE 6. Physical prototype

For the physical testing a special drop test machine has been utilized, with the test setup shown in Figure 7. Different orientations of the assembly have been tested, dividing the experimental testing in five different load cases. According to ISO 16750-3, three orientations have to be tested, and for this study two more unfavorable orientations are tested in order to acquire more information for the virtual model, as described in detail in the Introduction. For the testing, one prototype is used, starting with the most favorable orientation – LC1 continuing to the most unfavorable one LC5. After every drop the test piece has been examined for breakage and plastic deformation and orientation is selected in a way that no affected zone is in the endangered impact regions. A high-speed camera has been employed for capturing the experiments with 1000fps.

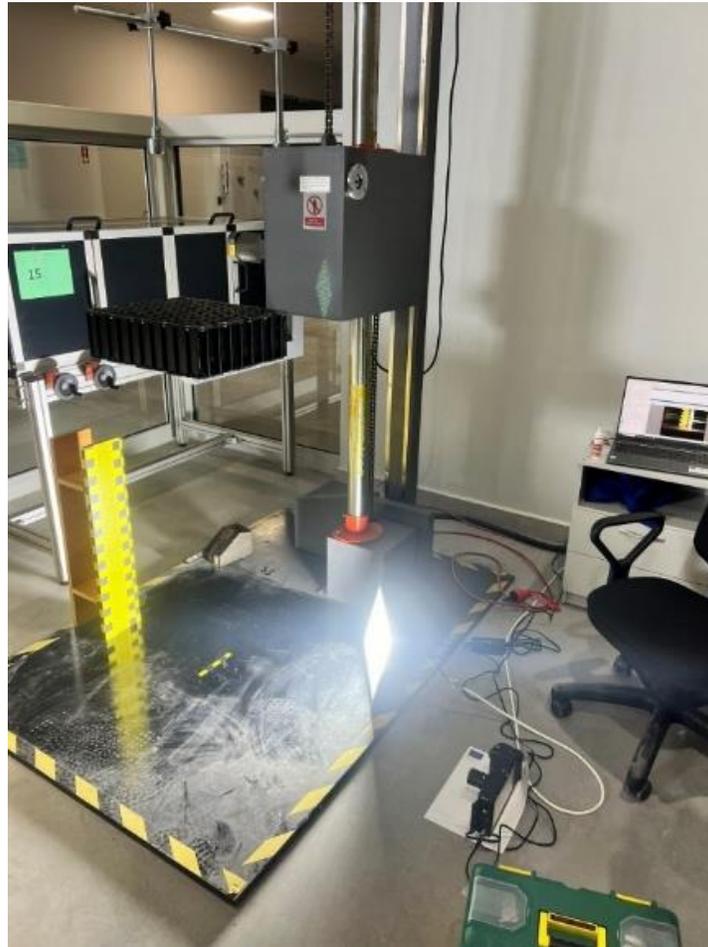


FIGURE 7. Test setup

After the conduction of the tests, footage and test protocols have been reviewed and analyzed, excluding LC3 and LC5 as previously mentioned. Mass breakage and shards separation are complex to model and not feasible for comparison and model validation. With the help of motion analysis software, rebound velocity and elastic deformation have been extracted for multiple points of the test piece in its different orientations and then used in the validation process of the virtual prototype. As previously mentioned, specific attention is paid to LC4, with its experimental velocity profiles shown in Figure 8, for one of the tracked points. This load case is selected for representation in the study due to its favorable viewpoint for visual analysis, while other load cases explained above have also been analyzed with the same approach. The nature and quantity of elastic strain can be observed and later compared with the virtual model for the validation purposes. The time of contact is indicated in Figure 8, instead of giving contact force, because it is more essential in terms of validation purposes. The moment of impact can be easily distinguished with a rapid shift in velocity direction and value.

LC4 Experiment

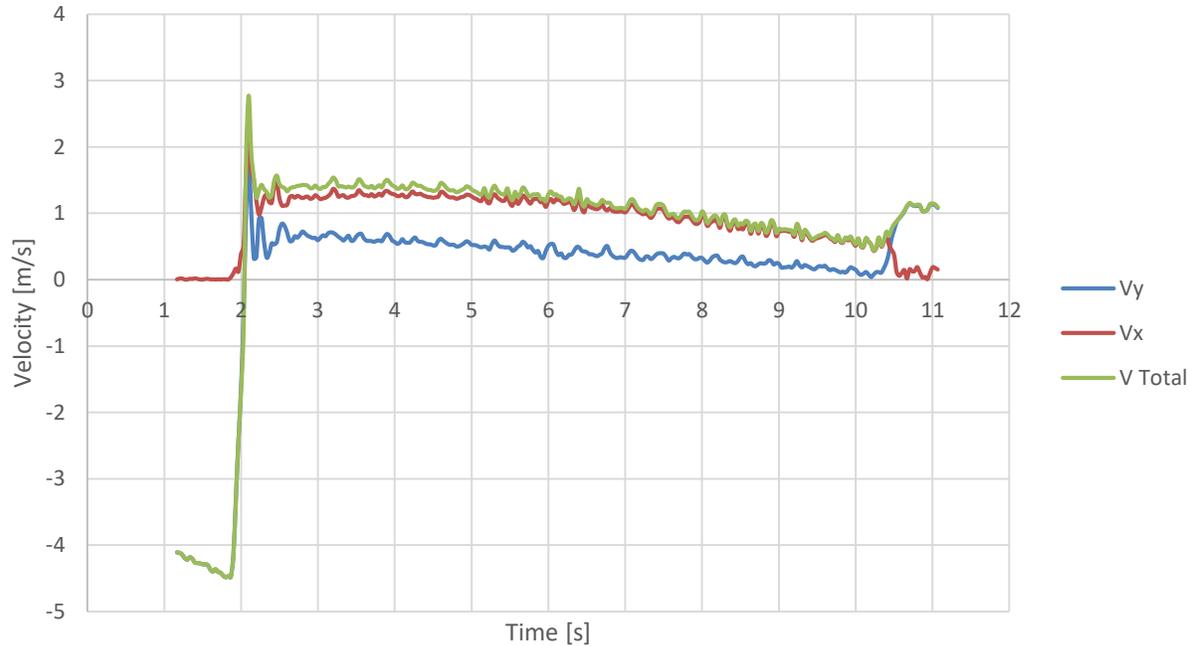


FIGURE 8. Experiment velocity profile for LC4

From Figure 8 it can be observed that a contact time of around 0.23s is observed and a rebound speed of 1,86m/s has been derived. It should be noted that in contrast with the virtual model, the resolution of the physical experiment is less accurate, which could potentially shift the maximum value and contact time, an effect predicted beforehand and it is determined that 1000fps would give sufficient enough data sampling for the goal of the study.

VALIDATION

For the validation process, planned criterions are rebound velocity, plastic and elastic deformation. Conclusions from the results comparison process can affect discretization, analysis settings and contacts, while boundary conditions, geometry and material properties are input data and are not to be altered. In this context, iterative improvements of the virtual model have been conducted in order to align it with the physical experiments. Rebound velocity is a marker showing the amount of energy lost in the impact, so it can also be defined by Coefficient of restitution (COR). The Coefficient of Restitution is a dimensionless parameter defined as the ratio of the relative velocity of separation after a two-body collision to the relative velocity of approach before collision. In most real-world collisions, the value of e lies somewhere between 0 and 1, where 1 represents a perfectly elastic collision (in which the objects rebound with no loss of speed but in the opposite directions) and 0 a perfectly inelastic collision (in which the objects do not rebound at all, and end up touching).

$$e = \frac{|v_b - v_a|}{|u_a - u_b|}$$

Where the two bodies are marked by a and b, the velocity before impact by u and the initial velocity after impact by v . In our case, the second body is the contact plate and its velocity is always equal to zero, so we are looking only

at the test object's velocity before and after impact. Hence, the simplified COR for an object bouncing of a stationary target, that is calculated in this case scenario is the following:

$$e = \frac{v}{u}$$

A rebound velocity in the Y4 direction (Fig. 4) for the experimental tests of 1.86 m/s has been recorded and 2.08 m/s for the virtual model, translating into COR of 0.42 (Experimental) and 0.47 (Virtual). Both values are highly plausible given the properties of the production material and the fact that the test subject is not a rigid body, but an assembly. Introducing joints and complex geometry decreases stiffness, hence increasing the energy absorbed in impact, lowering the COR (typical COR of ABS and PC plastics is 0.6-0.8 according to unofficial sources).

In the final comparison phase, a deviation of 12% is observed between experimental and computational data which is fully acceptable and this behavior is expected based on the several factors contributing to this deviation:

- Due to the method of the assembly bonding for the physical test subject, there are some differences in the virtual and experimental model. As previously explained, the tested unit is less rigid because of the production through rapid prototyping technologies, while for contact definition of the virtual model a bonded contact has been used, increasing rigidity, imposed from that it is the closest contact formulation in this case. In conclusion, the difference in the results follows the expected direction with a small deviation.
- Due to virtual model discretization and computational errors, small differences in results between iterations can occur. Additionally, as previously mentioned, discretization for the virtual model is more precise, giving possibility for accounting for even smaller spikes in velocity values.
- Perfect contact orientation for such a massive object is nearly impossible to be achieved due to test machine inaccuracies and mass center not aligning with the geometrical one. In the virtual model no rotation is configured as this would result in inaccuracies, the approach is to bring the experiment as close to the virtual model. Those inaccuracies result in creating unexpected rotations (resulting in rotation around the X axis, as shown in Figure 8), which in terms dissipates energy from the impact, lowering the COR (measured in the Y direction). In LC1 and LC2 due to the easier contact orientation the results deviation is less than 10%.

Contact time follows the presented factors, with around 0.1s for the virtual model and 0.23s for the physical experiment. Longer contact time naturally means more energy dissipated into the structure during impact, lowering the COR. The connection between those values is not linear, hence the results are plausible, additionally as previously mentioned with the different time sampling it is not accurate to compare those values, however their relative values are confirmed by the factors presented.

Comparing elastic and plastic deformation behavior and their values in the impact affected zone is also an applicable approach for validation of the virtual model. A sample elastic deformation in the virtual model for a selected point in LC4, shown in Figure 8 of 5.09mm compared to the one in the physical prototype of 5.28mm on the battery cover (which is composed of one part) shows a good correspondence in the results and follows the observed tendency of higher rigidity in the virtual model. Other observed load cases lead to similar results. The measured plastic deformation has a similar tendency and is approved to align within a 10% error gap.

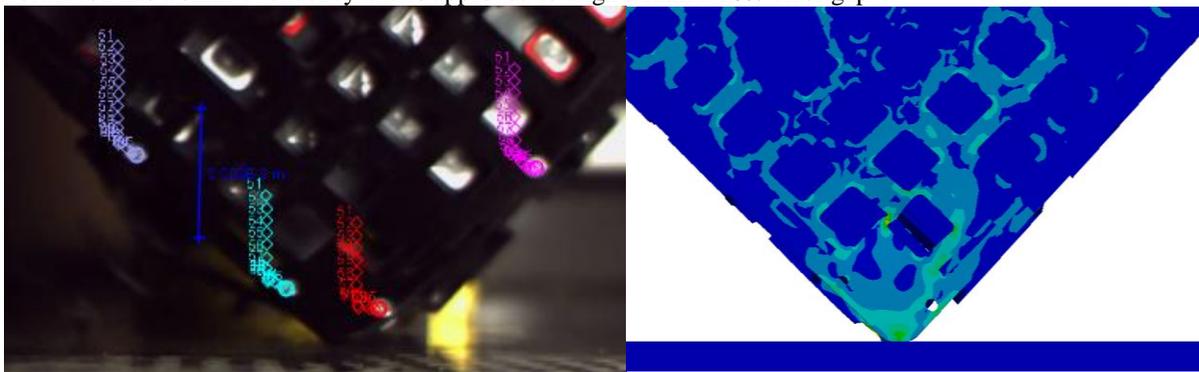


FIGURE 9. Motion analysis of LC4

It should be noted that the virtual and physical prototypes are not expected to behave exactly similar as per reasons defined above, data in the expected direction with a consistent deviation is sufficient for the validation of the complex virtual model for the goals of this study. Equal results from the comparison with the RP physical unit would mean discrepancies with the production unit. A

A final conclusion could be formed that there is a very good correspondence between the physical and the virtual prototypes for LC4. For LC1 and LC2 even smaller deviation has been observed (in parts due to the lower rebound speed), whereas for LC5 only deformation behavior is compared due to the angle of contact, causing rotation making validation through COR unfeasible. It is to be mentioned that all of the Load Cases virtual analysis are run with identical settings.

FINAL VIRTUAL PROTOTYPE

For the final virtual prototype, adjustments of the validated virtual analysis have been made, battery weights values have been set to the actual ones, battery connections and interface have been added. In some of the load cases the battery connections play a crucial role in the impact behavior of the battery module, as due to the high current requirements their cross section is significant. Stresses are transferred to them through the welded battery terminals, making those regions crucial for the safety except for the battery cells themselves. If some of these connections fail during mechanical influence, a shortage could occur which could result in a fire hazard. Due to the complexity of the analysis, only one LC4 has been computed, as the most unfavorable validated orientation.

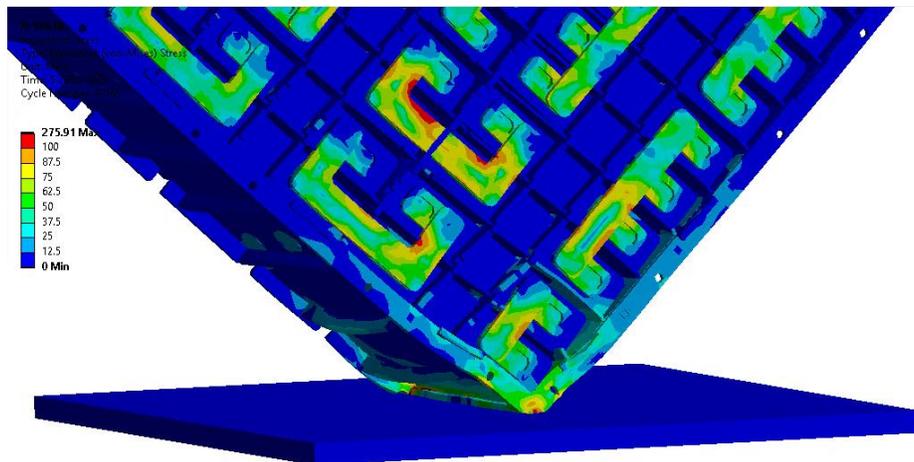


FIGURE 10. Zone of impact for LC4 for final virtual model

From Figure 10, the zone of impact can be observed, where plastic deformation of the edge and high stresses in some of the battery connections occur. Due to the plasticity of the materials, they are not exceeding 275MPa. Plastic strain for the battery connections is not exceeding 0.02%, meaning that no significant deflection would occur, as the geometry deflection is shown in Figure 10. As per expected, due to the copper's high plasticity, aluminum battery terminals are not significantly affected by the impact. Plastic strain for the housing however has a greater magnitude of 0.7% which would result in breakage, which is expected and inevitable. Stresses in the battery cells do not exceed 30MPa, which is an acceptable and safe value, meaning that no leakage would occur. The last criterion which is observed is the forces that occur in the contacts between the cells and the terminals and the terminals and the battery connections. Laser welding for these prototypes (studied outside the scope of this study) ensures a shear strength of 1kN and mechanical connections 2.5kN and a tensile strength of 1kN and 4kN respectively. In the virtual prototype contact forces do not exceed 110N meaning that a high safety factor is ensured for this criterion.

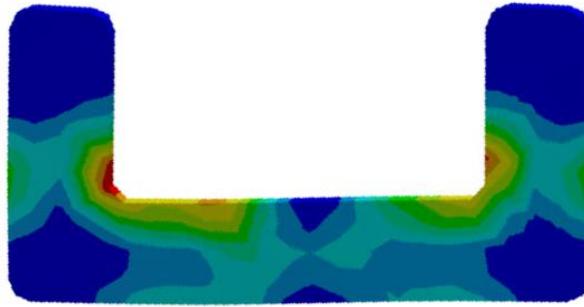


FIGURE 11. Plastic strain distribution in the most affected battery connection

In conclusion, the results from the computation show that no hazard would occur in the unfavorable and not according to standards mandatory LC4, respectively none are expected in the other load cases defined by the safety standards, validating the initial design in the context of an impact influence – drop test.

CONCLUSIONS

A methodology for impact testing a complex assembly has been developed, including experimental testing of the physical unit produced by rapid prototyping technologies used for virtual prototype computational FEA validation and a final virtual FEA simulation to ensure safety performance according to corresponding standards. Five different load cases have been experimentally examined, excluding two based on predefined criteria. The three valid load cases have been transferred in a virtual environment and the impact has been simulated using explicit dynamics finite element analysis. During the validation phase experiments have brought results with a very good level of confidence for the virtual prototype to be validated. Some deviations within the acceptable range in the virtual and experimental results for one of the Load Cases are correctly expected and then observed in correspondence with the presented in the validation phase factors. Alterations of the validated virtual prototype have been introduced in order to ensure compliance with the production device which is subject to impact tests. Results from the final virtual analysis have shown that with a high safety factor, no hazard would occur in case of the studied impact influence – drop test.

In conclusion, in this work an initial prototype has been used to analyze certain features of the finished product in order to plan any design alterations. The presented methodology is a powerful tool for impact analysis of a complex prototype geometry, due to the production lifecycle of new products. The predefined goals of this study are met, predicting the model's behavior in crucial areas of concern during test procedures with corresponding standards allowing for financial and time resource optimizations.

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