

# CAE Method for Evaluating Mechanical Performance of Battery Packs under Mechanical Shock Testing

Yongcai Wang, Rajaram Subramanian, Sarav Paramasivam, and George Garfinkel  
Ford Motor Company

## ABSTRACT

Mechanical shock tests for lithium metal and lithium-ion batteries often require that each cell or battery pack be subjected to multiple shocks in the positive and negative directions, of three mutually perpendicular orientations. This paper focuses on the no-disassembly requirement of those testing conditions and on the CAE methodology specifically developed to perform this assessment.

Ford Motor Company developed a CAE analysis method to simulate this type of test and assess the possibility of cell dislodging. This CAE method helps identify and diagnose potential failure modes, thus guiding the Design Team in developing a strategy to meet the required performance under shock test loads. The final CAE-driven design focuses on the structural requirement and optimization, and leads to cost savings without compromising cell or pack mechanical performance. As an example, this method is applied to Ford Motor Company's current generation of air-cooled, prismatic cell lithium-ion Plug-in Hybrid Electric Vehicles (PHEVs). Physical testing performed on the final optimized design correlated well with the CAE results thus providing validity to the simulation methodology.

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## INTRODUCTION

Robustness against mechanical shocks, vibration, and other aggressive conditions acting on battery packs is an important consideration during the battery design process. Mechanical shock is addressed as part of several testing specifications as well as regulatory requirements and procedures, such as: UN38.3 [1], [2], [3], USABC Mechanical shock test in Electrochemical Storage System Abuse Test Procedure Manual [4], Battery electric vehicle safety of ECE R100.02 [5]; Safety Test for Traction Battery of KMVSS [6].

A shock test procedure determines whether a multiple-direction shock test may cause dislodging of any parts in the traction battery pack or arrays when shock tested under a given impact or "g" load for a given load duration and for different battery or cell sizes. Usually, cells and batteries are classified based on their gross mass.

The battery pack in Ford Motor Company's current generation PHEVs is used as an example to establish the CAE shock test method. The pack is shown in Figure 1. This PHEV battery pack is used in Ford C-Max Energi and Fusion Energi vehicle platforms. The thermal management strategy is cabin air-cooled configuration. The gross weight of the battery pack is approximately 118kg. For this example, the PHEV battery pack is subjected to repeated 55 g level shocks, with 11ms duration in each pulse.

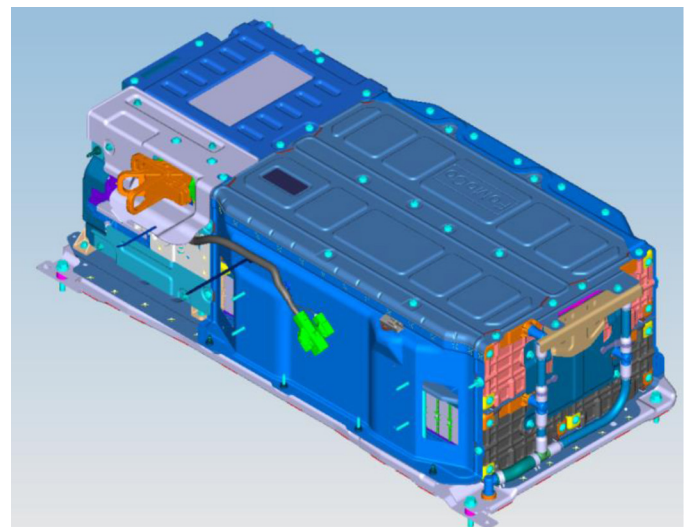


Figure 1. Ford Motor Company's current generation PHEVs battery pack

## CAE MODEL SETUP

Lithium-ion cells are the core component of this battery pack and those cells exhibit complex mechanical behavior between beginning of life (BOL) and end of life (EOL). During array builds the cells are compressed to ensure adequate cell performance during the intended

pack service life. As cells age during the battery life cycle, cells tend to bulge until EOL due to internal content chemical - electrical reactions. The self-bulging effect of the cells is one of the key factors that influence the structural strength of the battery pack design. Also, the internal cell jelly roll's mechanical properties show very strong, non-linear structural resistance when compressed. Though mechanical shock testing is usually conducted at the cell's BOL state, the array structure must be designed to withstand EOL cell bulging forces. In order to accurately represent these behaviors in the CAE analysis, a proper self-bulging cell CAE model was developed by the Ford Motor Company Electrified Powertrain Engineering (EPE) department.

For better correlation purposes, an array level investigation CAE analysis has been conducted to find out the relationship between compression force (which is equivalent to bulging force) and rail separation aftershocks. Figure 2 shows the rail separation for a particular prismatic cell array after cross-array direction consecutive shocks in both positive and negative directions. The center span deformation or bowing (initially parallel), indicated by a yellow dual arrow in Figure 2, is the result of cumulative plastic deformation of metal parts after six consecutive shocks. By performing a CAE simulation, the central rail separation distance change can be derived from the CAE displacement contour curves, shown in Figure 3.

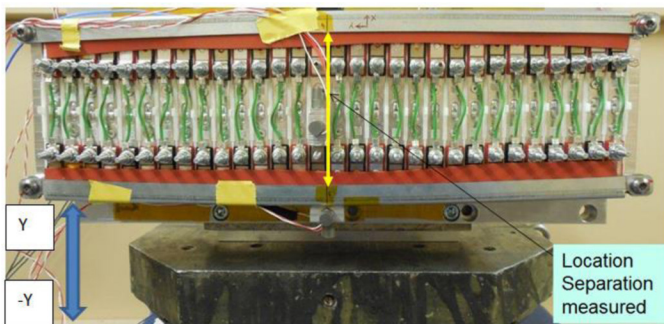


Figure 2. Rail separations after shock tests in both  $\pm Y$  directions

Figure 3 shows a typical CAE simulation contour at a given self-bulging force. During three +Y direction shocks, the maximum deformation and peak displacement of the +Y side rail continuously increases, as shown in the upper-right graph in Figure 3. The -Y side rail shows delayed -Y direction deformation due to cells bouncing back after each impulse load, but the deformation is insignificant because the elastic deformation is dominant. In the following three -Y direction shocks, the situation is reversed except that the +Y side rail permanent deformation is retained.

The relationship of cell self-bulging force vs cell array rail separation during the shock test CAE simulation is shown in Figure 4. The curve indicates that the self-bulging force provides a significant contribution factor to the rail separation. The rail separation is the root cause of the cell dislodging during shock test. Once the self-bulging cell CAE model is tuned to correlate with the physical test, it can be introduced into the global battery pack CAE model for full pack or array shock test simulations.

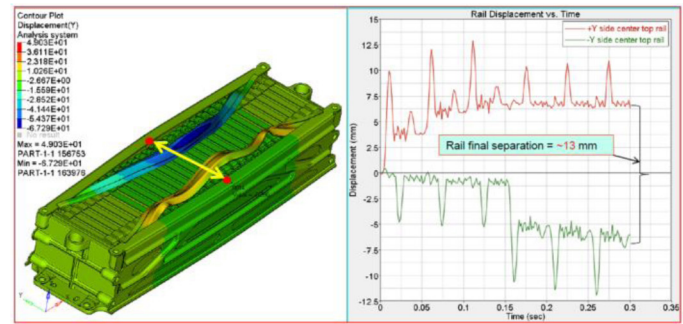


Figure 3. Rail separation CAE shock tests in both  $\pm Y$  directions

The testing sequence for multiple shock directions is not usually specified in shock test specifications. Thus, the test could be performed in any combination of testing directions. For pack level shock tests, detailed battery cells and spacers are required to be present in the CAE model. That accounts for a large amount of the total element count in the model. Running the successive shock simulations with interval rests as specified in typical specifications, exceeds the capacity of currently available computing simulation resources for large battery pack models. Instead, single shock in multiple directions can be performed as individual events. It is recommended that low strain, relatively conservative, stress-strain curves obtained from quasi-static tensile testing be used in the CAE analysis to compensate for the plastic strain accumulation in successive shock tests. The simulation methodology can be reverted back to successive/ cumulative shocks when more powerful computer resources become available in the future, or if the model size can be kept relatively small.

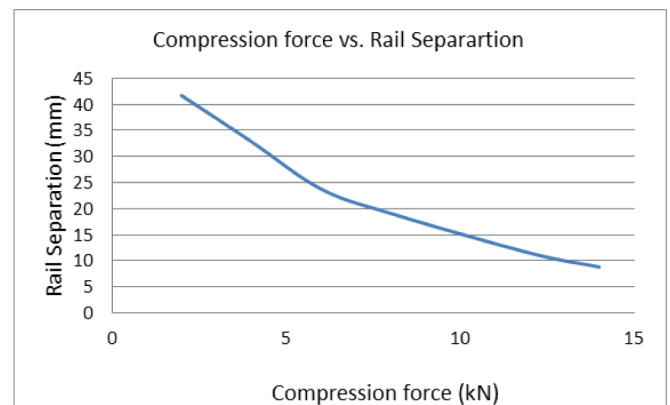


Figure 4. Compression forces vs. battery array rail separation

ABAQUS/EXPLICIT version 6.12 [7] was used for the shock analysis. Other dynamic nonlinear analysis software programs that include material and geometry nonlinearities, as well as contact can also be chosen for this simulation. The running model should include all structural components like sheet metal parts, molded parts, and casting parts. Non-structural parts like electronic apparatus (e.g., control modules, charger, etc.) should also be included in the whole battery pack model. Wire harness, connectors, and labels can be ignored.