

Development and Manufacturing of Multifunctional Structures for Automotive Vehicles

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ABSTRACT

The introduction of electric vehicles (EVs) has posed many technical challenges to the automotive industry. State-of-the-art lithium-ion (Li-ion) batteries add significant weight to vehicles both in the form of battery weight and supporting systems, immensely hindering vehicle performance and efficiency. A primary source of the penalty is that battery packs and supporting systems each serve only one purpose, e.g. energy storage or cooling, as current EV battery cells do not carry structural loads or absorb collision impact energy.

The Department of Energy Vehicles Technologies Office (DOE VTO) has interest to research, develop, and validate a new class of multi-functional (composite) materials and structures. To meet the DOE requirements, the team lead by Acellent Technologies Inc. along with Senvias has proposed the development of an **innovative energy storage solution**. The solution utilizes *Multifunctional Energy Storage Composite (MESC) structures* originally developed at Stanford University and exclusively licensed by Acellent that:

- A. Supplies electrical power, while serving as a structural element, capable of carrying mechanical loads with reduced weight and complexity
- B. Uses embedded sensor networks to monitor the state and health of both the composite structure as well as the battery (Battery Health Monitoring, BHM) on a real time on demand basis

MESC's are an optimized design of a robust multifunctional hybrid-composite-battery-chassis system that can carry structural loads, safely store electrical energy, absorb impact energy, and lead to significant weight savings. The goal of the DOE project is to develop the end-to-end manufacturing process for MESC structures to be used in ground vehicles. A composite enclosure together with the MESC will be designed and prototyped by the end of the project. This paper will provide the details of the development for the project towards the design of the MESC and BHM for use with an automobile enclosure.

INTRODUCTION

The objective of the DOE project is to research, develop, and validate a new class of multi-functional (composite) materials and structures that supply electrical power while serving as a structural element capable of carrying mechanical loads with reduced weight and complexity, and use embedded sensor networks to monitor the state and health of both the composite structure and battery in real-time to increase battery system specific energy capacity (Wh/kg) > 60%. The goal of the project is to develop the end-to-end manufacturing process for MESC structures to be used in ground vehicles. A composite enclosure together with the MESC will be designed and prototyped by the end of the project. This paper summarizes the preliminary design for the MESC for ground vehicles.

MULTI-FUNCTIONAL ENERGY STORAGE COMPOSITES (MESC)

MESC encapsulates lithium-ion battery materials inside high-strength carbon-fiber composites and use interlocking polymer rivets to stabilize the electrode layer stack mechanically ([1], Figure 2). These rivets enable load transfer between battery layers, allowing them to store electrical energy while also contributing to the structural load carrying performance, without any modifications to the battery chemistry. Previous experimental results by [1] indicate that the MESC offer electrochemical performance comparable to standard lithium-ion cells, despite the disruptive design change.

The mechanical performance of MESC was assessed via quasi-static three-point bending tests, with results showing significantly improved mechanical stiffness and strength over traditional pouch cells. The rivets minimize interlayer shear movement of the electrode stack, thus allowing it to maintain electrochemical functionalities while carrying mechanical bending. While minimal load application can cause permanent deformation of pouch cells, MESC maintain their structural integrity and energy-storage capabilities under realistic repeated loading.

Testing [1] has demonstrated the mechanical robustness of MESC, which allow them to be fabricated as energy-storing structures for electric vehicles and other applications. MESC structures can therefore represent a novel form of multifunctional structural battery materials that can carry mechanical loads while simultaneously providing energy-storage capabilities. MESC provide a disruptive integration technique that allows high-energy Li-ion battery electrode materials to be embedded in high-strength carbon-fiber-reinforced-polymer (CFRP) composites.

The novelty of MESC lies in their incorporation of through-thickness interlocking polymer ‘rivets’ that extend through carefully designed perforations in the battery stack to interlock the electrode layers and securely anchor these layers onto the structural CFRP facesheets. Standard industry electrodes can be adapted to function directly within this design without any requirement for battery chemistry modifications, which may be crucial for industry adoption.

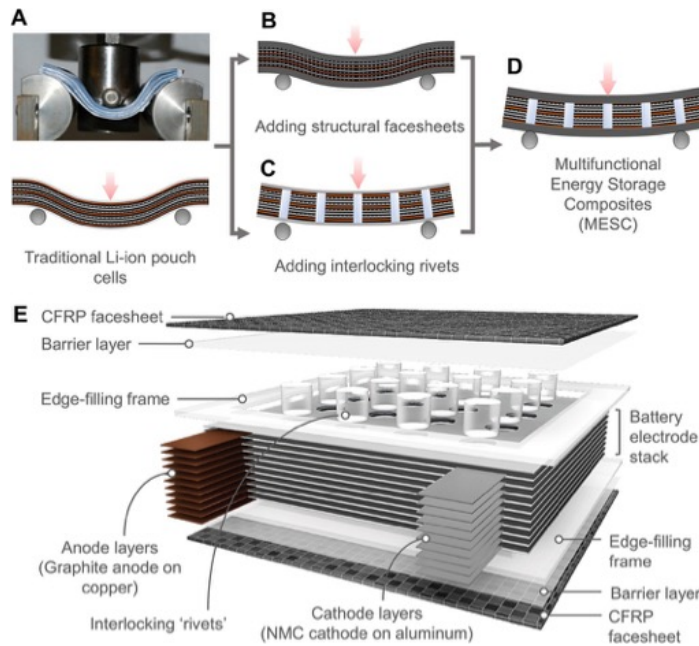


Figure 1. A-D) Mechanical comparison between MESC and typical Li-ion pouch cell. A) Pouch cells consist of loosely-laminated, thin electrode layers that provide minimal resistance to mechanical loading, similar to a loose deck of cards; B) and C) show intermediate steps to enhance the structural robustness of Li-ion cells by addition of structural facesheets and interlocking rivets as separate solutions; D) MESC use through-thickness rivets to interlock the sandwiched battery stack. These rivets inhibit shear movement of the layers while enabling load transfer through the core. The battery can thus contribute to the mechanical load-carrying performance. E) 3D schematic illustration of MESC. An array of through-thickness rivets is used to interlock a stack of typical Li-ion battery electrodes three-dimensionally. These rivets are securely anchored on the encapsulating carbon-fiber-reinforced- polymer (CFRP) facesheets, allowing the entire unit to act as a mechanically-efficient sandwich structure. (Adopted from Ref[1])

MESC DESIGN AND ANALYSIS

The overall design of the MESC structure for vehicles is based on the target electrical power capacity. The target is to increase battery system specific energy capacity (Wh/kg) > 60%. Figure 2 shows the target energy capacity based on the current trend [2]. The baseline was identified as 112 Wh/kg while the target based on the 60% increase would be 180 Wh/kg. the MESC design was therefore oriented towards meeting this target.

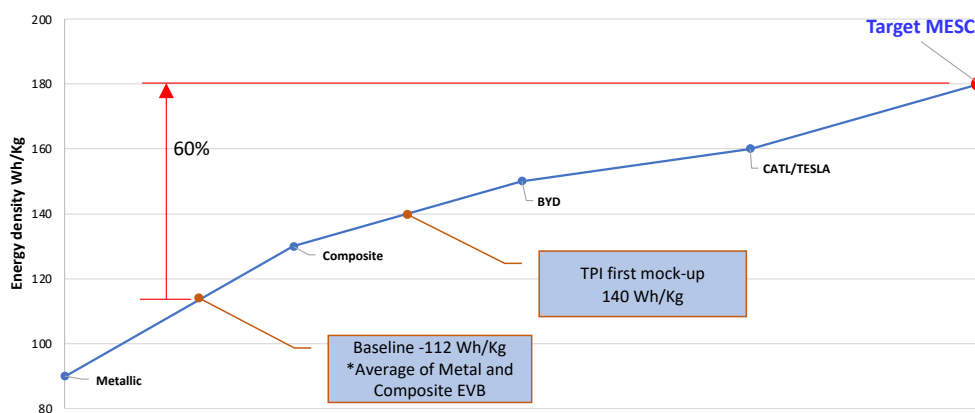


Figure 2. Targeted energy capacity for the MESC design

The MESC enclosure will include several components as shown in figure 3. Based on these components, a preliminary design for the MESC and enclosure was created as shown in Figure 4.

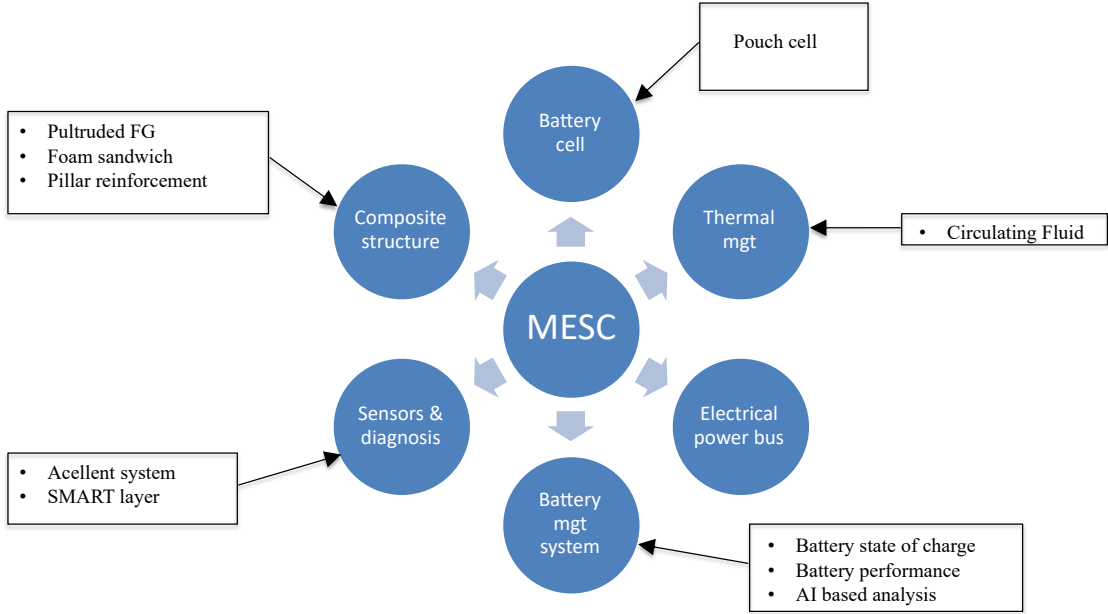


Figure 3. Components in the MESC design

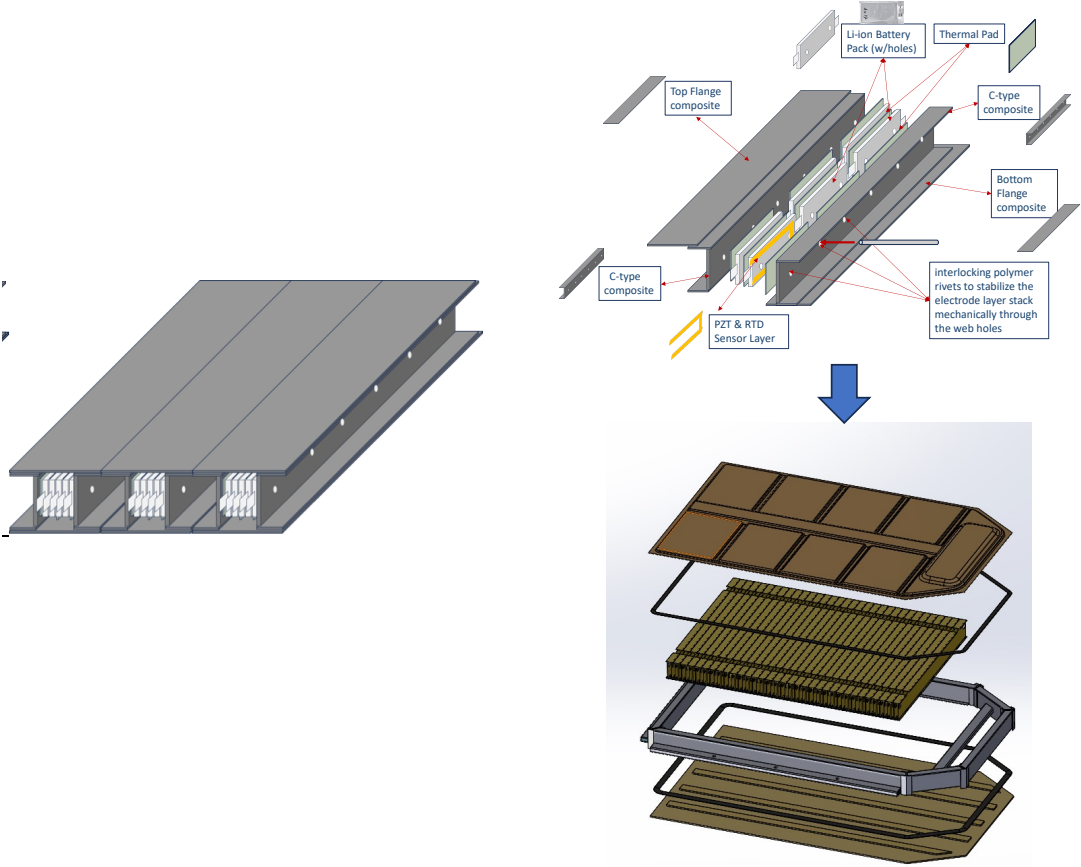


Figure 4. Preliminary design

The enclosure design is shown in Figure 5. The geometrical design and preliminary dimensions were also developed.

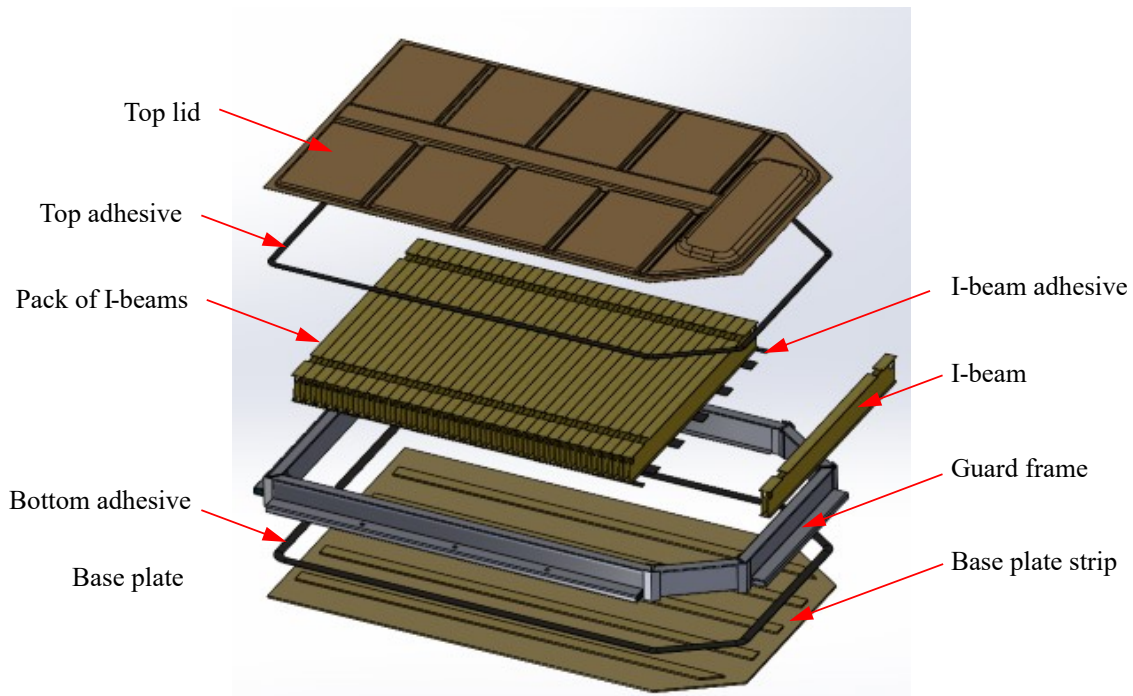


Figure . Components of the enclosure

MESC SIMULATION

For the MESC an I-beam design was compared to a C-channel design. Two configurations were constructed using the same two C- channels (Figure 6). Configuration I: C channels back-to-back, Configuration II: Two C channels arranged as I beam. Higher load capacity and stiffness were identified for configuration II (~5/3 times configuration I). Therefore, the I-beam design will be used in all future MESC design considerations.

The I-beam MESC design will be incorporated into the preliminary pack design as shown in Figure 5. Based on the energy requirements and the number of batteries needed the number of I-Beams will be needed to carry the total number of required batteries.

Various loading cases were considered to design the I-Beam and come up with optimum design parameters for the I-Beam battery assembly. With twisting and torsion loading being the two main loading scenarios for the I-Beam, the simulations were performed on the I-Beam battery assembly with the corresponding test cases.

Parametric studies on the battery-I Beam assembly were performed to study the influence of various parameters on the stiffness of the structure. The number of batteries and the wall thickness of the I-Beam were considered as the parameters for the analysis. The thickness and number of battery parameters of the I-Beam will be optimized for the maximum stiffness/weight of the structure. A symmetric model of I-Beam was developed and 3mm thickness was considered for the I-Beam. Eight batteries per I-

Beam were assumed and bending applied at edges. Force vs. deflection curve was obtained for the configuration as shown in figure 7(a). Torsion was applied at the edges of the I-Beam and Force vs. deflection curve was obtained for the configuration (Figure 7(b)).

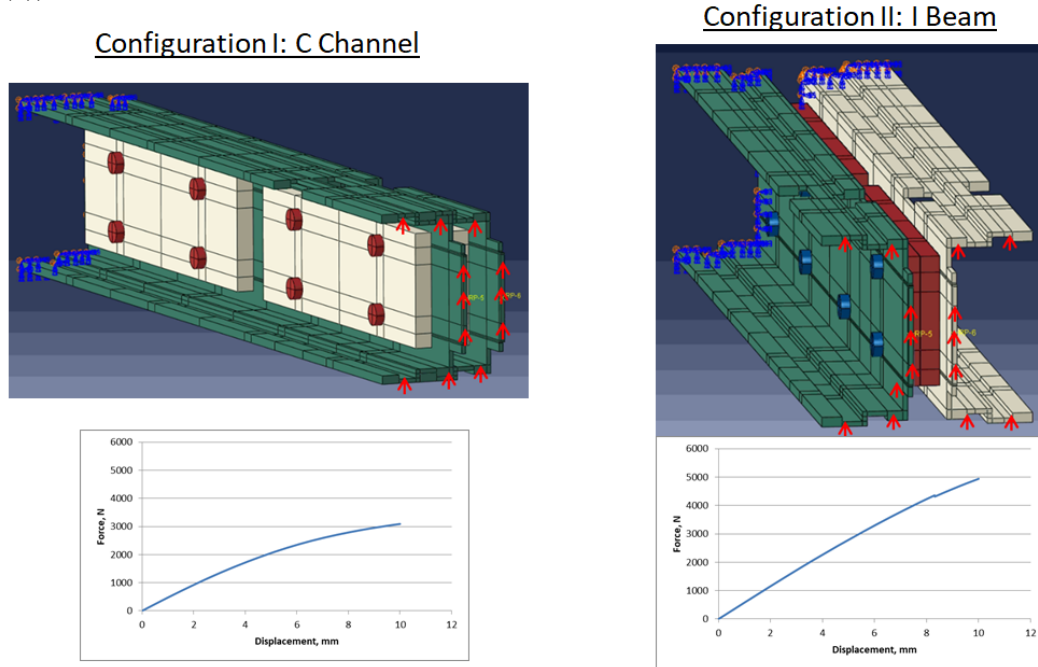


Figure 6. C-channel Vs I-beam design

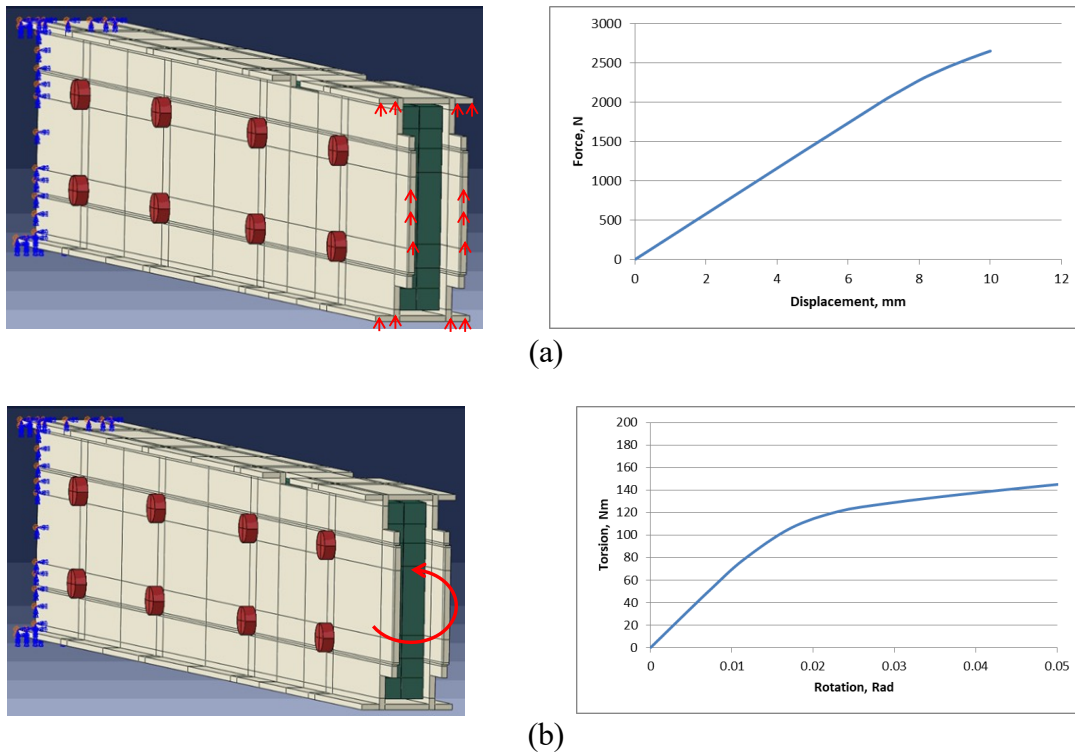
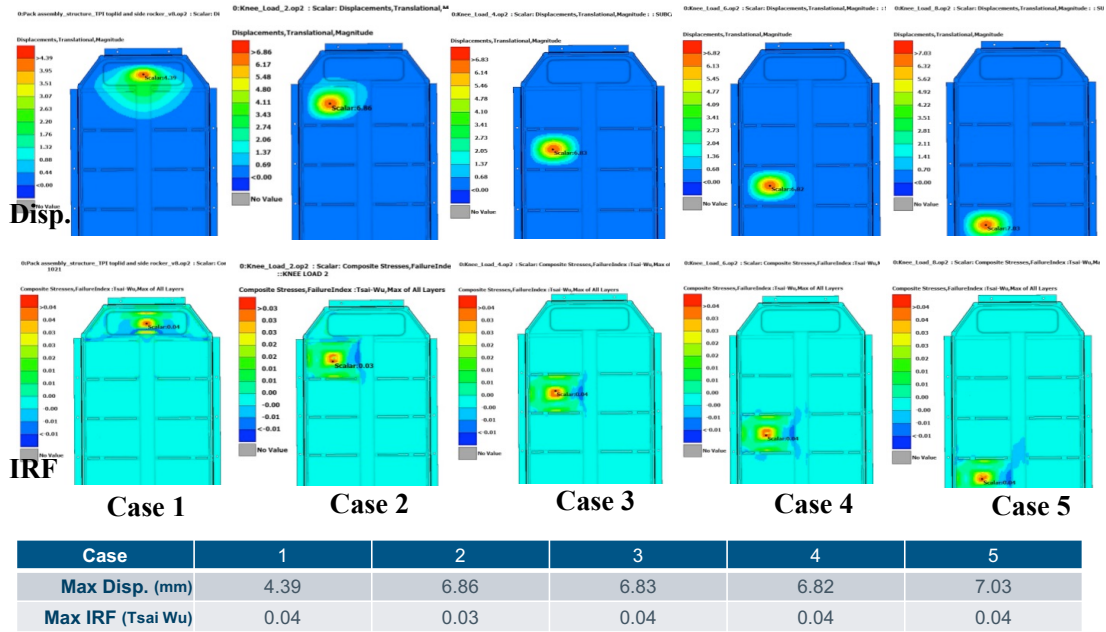
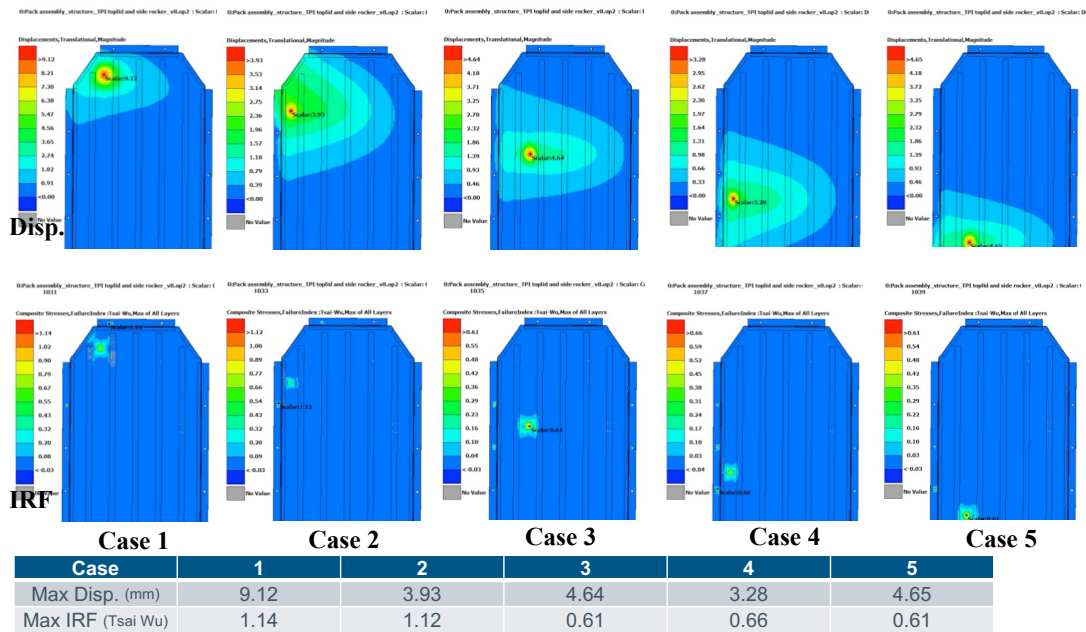


Figure 7. Bending & Torsional loads

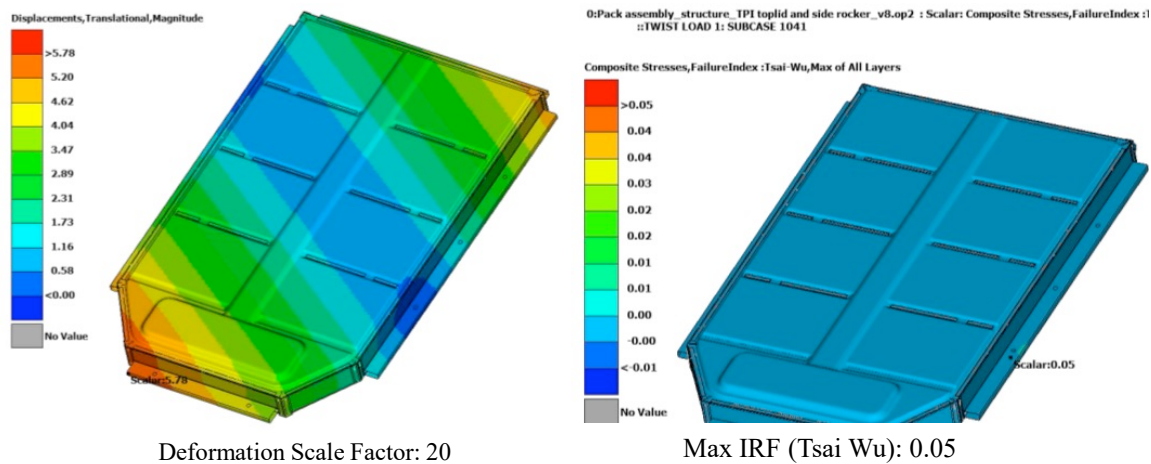
Finite Element analysis (FEA) was also successfully conducted on the enclosure design based on several load cases and EV requirements including Lifting Load, Knee Load, Jack Load, Twist Load, Modal Analysis, Internal Pressure, Shock Load, Stone Impact, Battery pack drop, Side Impact, Front Impact. Figure 8 show some of the various testing configurations.



(a) Knee load



(b) Jack load



(c) Twist load

Figure 8. Example of tested load cases for EV's

SUMMARY

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A model of the battery- Enclosure and MESC I Beam assembly was constructed and structural bending and torsional analysis were studied in the assembly. A parametric study on the assembly was simulated to study the effect of thickness and number of batteries on the I-Beam assembly. Load cases on the enclosure were designed and simulated.

Further analysis on the thickness and number of batteries based on the strength requirement of the I-Beam will be conducted to identify the number of batteries the I-Beam can hold and the thickness of the I-beam. In the future the complete process to increase battery system specific energy capacity (Wh/kg) > 60% will be created and the end-to-end process for MESC structures to be used in ground vehicles developed.

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