Materials Research Proceedings 44 (2024) 465-474 https://doi.org/10.21741/9781644903254-50

Lightweight battery enclosure design

GANGULI Tanmay[1,a *] and DATE Prashant P.[1,b]

[1]Dept. of Mech. Eng. Indian Institute of Technology, Bombay Powai, Mumbai, India

[a]tanmayganguli09@gmail.com, [b]ppdate@iitb.ac.in

Keywords: Light Weight Battery Enclosure, Taguchi Orthogonal Arrays, Design of Experiments, Optimization

Abstract: The battery box is the heaviest part of an electric vehicle and may account for 20-30 per cent of its weight. Therefore, the design of a lightweight battery box is an important step towards the lightweight design of the entire vehicle. In this paper, a systematic procedure has been followed to reduce the weight of a given battery enclosure structure, while ensuring that the structure can withstand the stresses during acceleration, braking and turning of the vehicle, and the compressive stresses on the cells inside the enclosure do not exceed the maximum limit. The important design parameters were identified, and an optimal parameter set with respect to lightweight design and structural stability was determined. The Taguchi method of orthogonal arrays was used for the analysis to optimize the calculation efforts. The stress distribution over the body of the enclosure was analyzed and material was removed from the regions having low stress concentration. Subsequently, the structure was modified and forced air cooling was introduced to ensure that the temperature rise during operation was within acceptable limits. The stress, thermal and modal analysis of the resultant structure was then carried out to demonstrate its feasibility.

Introduction

The use of batteries for various applications has become extremely important to replace conventional fossil fuels. This is specifically pertinent in the case of vehicles, where the design of batteries and the battery pack enclosure (BPE), is of great importance not just for the safety of operation of the batteries but also to reduce the weight and consequently the efficiency of the complete system. It is estimated that ~ 20-30% of the total weight of a battery electric vehicle is contributed by the BPE structure. Thus, novel designs and their implementation to reduce the weight of BPEs has been an important area of research by numerous groups in the recent past. [1,2,3]. Another approach is to combine the design novelties for weight reduction with the use of lightweight and high strength materials for the construction of the BPE structures. Qiu-Sheng Chen et al. have used Aluminum alloy in place of mild steel to design the BPEs [4]. Chen et. al have reported the use of carbon fiber reinforced plastics as battery case and Aluminum alloy as frame structure [5]. Battery operation also generates a lot of heat and hence, thermal management is also an important issue for the safe operation of batteries. Passive management techniques have been reported by Parsons et al. [6] and active cooling by the flow of forced air has also been reported [7]. Thus, in this work, an approach to reduce the weight of a given battery pack enclosure is presented, with a resulting optimized structure design that is structurally robust (shown by stress and modal analysis) that also allows for efficient heat transfer out of the BPE.

Procedure overview

We have used two main approaches towards optimizing a given structure with regards to weight reduction: topology optimization and parametric optimization. Topology optimization aims at removing material from the given body from low stress areas, while ensuring its mechanical and structural robustness to applied forces and stresses, etc. Parametric optimization on the other hand identifies certain parameters in the body design (e.g. thickness of a battery box) and aims to tune

Materials Research Proceedings 44 (2024) 465-474 https://doi.org/10.21741/9781644903254-50

those parameters to obtain the desired objective, which in this case is weight reduction. First, we identified relevant parameters and optimized them. However, the resulting battery box structure was found to be thermally infeasible as the temperature of the cells was found to reach very high values in a steady state thermal analysis. Thus, the original structure had to be modified to account for a thermal management system. The battery box structure was suitably modified to allow for air cooling and parametric optimization was repeated. The feasibility of the new battery box structure both mechanically and thermally was checked through simulations. Once the structure was finalized, low stress regions in the enclosure were identified by inspection of the stress distribution and material was removed from those regions (topology optimization). Structural simulations were repeated to ensure mechanical robustness. Further practical feasibility was ensured through modal analysis of the BPE. In all the simulations, only the cells and enclosure were considered. All other components of the battery pack like battery management system, thermal management apparatus, etc. were not considered. All simulations were carried out using ANSYS 2024 (student) and 2016 versions. The CAD models were designed in SOLIDWORKS 2019.

Parametric Optimization of Given Structure

Initial Structure. The initial battery box structure is given in Fig. 1. The properties of the battery box and pouch cells used for the simulations are listed in Table 1. The bulk properties of pouch cells have been reported in previous works [8]. The boundary conditions applied on the battery box are summarized in Table 2. The box was subjected to an acceleration of g (gravity) in -Y (vertical) and 3g in either X or Z axis (signifies acceleration, braking, rapid turning), where the axes are as shown in Fig. 1. The bottom edges were assumed to be attached to the surface on which the box was kept, by a fixed joint. Similar boundary conditions are considered by other authors [4]. Five parameters of the battery box design were identified: enclosure wall thickness, cell gap, cell-separator wall height, middle partition thickness and base plate thickness, which were optimized in this work.

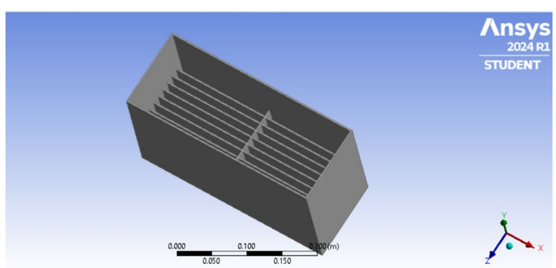

Fig. 1. Initial battery box structure.

Table 1. Properties of the initial battery box and Properties of each pouch cell.

Mass	7.67 Kg
Material	Structural steel
Size	20 x 2 cells
Enclosure thickness	2 mm

Size	200 x150 x10 mm^3
Mass	500 g
Eff. Young's modulus	4.2 GPa
Poisson's ratio	0

Table 2. Boundary conditions.

Accelerations considered in the calculations	a) 30 m/s^2 along X and -10 m/s^2 along -Y b) 30 m/s^2 along Z and -10 m/s^2 along -Y
Support	Bottom 4 edges fixed
Displacement	No Y displacement

Taguchi method of Design of Experiments

Techniques like multiobjective genetic algorithm (MOGA), particle swarm optimization (PSA) etc. have been used for parametric optimization [9]. A simpler approach is to consider various 'levels' of each parameter and try out different combinations to reach an optimal parameter set. A full factorial design method where the complete parameter space is explored is extremely time consuming. A faster way to design experiments is by using orthogonal arrays [10]. For our case, three levels for the five parameters were identified (Table 3). Thus, an L-18 Taguchi orthogonal array can be constructed, reducing the number of experiments needed from 3^5 to just 18 [11]. For each case, the mass of the box, maximum and average stress, and maximum and average deformation for both acceleration directions were tabulated (Table 4).

Table 3. Optimization parameters and their levels.

Enclosure thickness (a)	2 mm (1)	1 mm (2)	0.5 mm (3)
Base thickness (b)	2 mm (1)	1 mm (2)	0.5 mm (3)
Cell gap (c)	2 mm (1)	1 mm (2)	0.5 mm (3)
Middle partition thickness (d)	2 mm (1)	1 mm (2)	0.5 mm (3)
Cell separator height (e)	100 mm (1)	80 mm (2)	50 mm (3)

Results

We find that the maximum stress and deformation values for all the simulations are within acceptable bounds, much lower than the yield strength of structural steel, which is around 240 MPa. Experiment 16 gives the lightest battery box weight (1.7 kg). The results for all the combinations are summarized in Table 4. The stress distribution in the structure for 4 cases, namely: a) Stress distribution in the original battery box for acceleration in +Z direction, b) Stress distribution for acceleration in +X direction, c) Stress distribution for Experiment 16, acceleration in + X direction, and d) Stress distribution for Experiment 16, acceleration in +Z direction; are shown in Figs. 2a, 2b, 2c and 2d respectively. Thus, we can get the optimal lightweight structure from the combination of these parameters. This weight is around 1.7 kg, thereby reducing the weight by over 80% from the initial assumed structure.

Table 4. The summary of the results of max stress, max deformation and mass for each factor-level combination of the L-18 orthogonal array.

Expt. No	t_ side(a)	t_ bottom(b)	t_ cell(c)	t_ cent(d)	h_ part(e)	max stress (MPa) (x accl, z accl)	max deform (mm) (x , z)	Mass (kg)
1	2	2	2	2	100	3.27,5.52	0.017,0.043	7.667
2	2	1	1	1	80	4.68,18.93	0.02,0.085	4.63
3	2	0.5	0.5	0.5	50	9.18,37.6	0.057,0.18	3.245
4	1	2	2	1	80	4.81,13.42	0.023,0.08	5.3
5	1	1	1	0.5	50	12.98,43	0.06,0.183	2.64
6	1	0.5	0.5	2	100	5.87,7.75	0.014,0.06	2.63
7	0.5	2	1	2	50	8,9.43	0.055,0.18	2.31
8	0.5	1	0.5	1	100	6.5,10.76	0.017,0.05	2.03
9	0.5	0.5	2	0.5	50	7.1,27.64	0.056,0.17	2.94
10	2	2	0.5	0.5	80	8.44,26.12	0.23,0.084	3.97
11	2	1	2	2	50	5.46,9.54	0.056,0.16	5.17
12	2	0.5	1	1	100	3.15,13.76	0.016,0.046	4.94
13	1	2	1	0.5	100	3.7,21.32	0.017,0.048	3.98
14	1	1	0.5	2	80	9.2,13,82	0.022,0.085	2.51
15	1	0.5	2	1	50	8,20.14	0.057,0.165	3.63
16	0.5	2	0.5	1	50	12.16,25.46	0.058,0.18	1.7
17	0.5	1	2	0.5	100	3.8,15.47	0.018,0.047	5.23
18	0.5	0.5	1	0.5	80	5.23,20.2	0.023,0.087	2.5

Thermal simulations

Apart from the structural simulations, the thermal feasibility of this structure also must be checked. It is unlikely that conduction along with natural convection in the surrounding air will be sufficient to keep the cells within the desired temperature limit. The desired temperature limit of a pouch cell is 40-50°C [12]. Pouch cell thermal properties such as specific heat, thermal conductivity and heat generation rate have been reported [13]. The parameters used in our simulations are summarized in Table 5. Steady state thermal analysis was performed, with only natural convection in the ambient air and conduction into the battery enclosure as the modes of heat dissipation. It was observed that temperatures of the cells became too high for the original design (Fig. 1), as shown in Fig. 3, and the simulation failed to converge for many of the cases with thinner cell separation. Obviously, the structure by itself cannot maintain the cell temperatures in the desired range. Thus, thermal management is required, along with weight reduction.

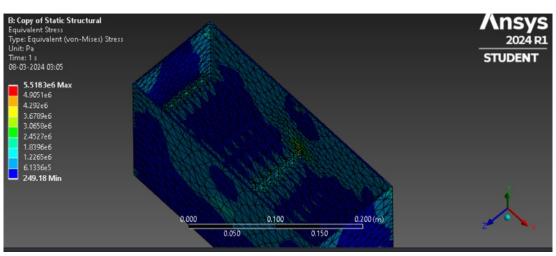

Fig. 2a. Stress distribution of original battery box for acceleration in +Z direction.

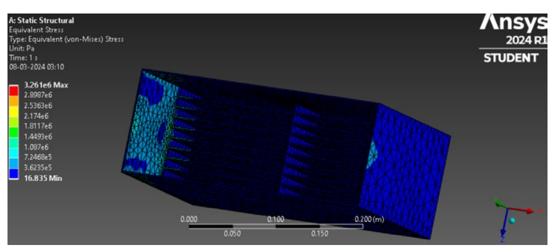

Fig. 2b. Stress distribution for acceleration in +X direction.

Materials Research Proceedings 44 (2024) 465-474 https://doi.org/10.21741/9781644903254-50

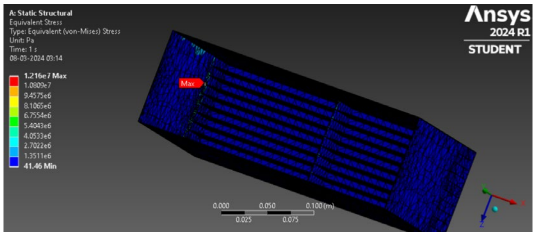

Fig. 2c. Stress distribution for Expt. 16, acceleration in +X direction.

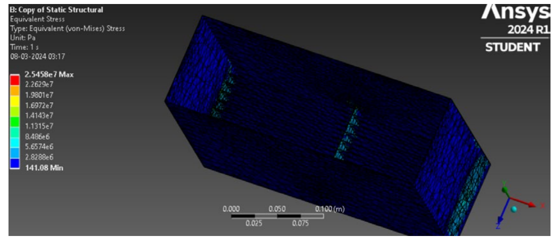

Fig. 2d. Stress distribution for Expt.16, acceleration in +Z direction.

Table 5. Properties of pouch cells used in thermal simulations.

Specific heat	550 J/kg-K
Thermal conductivity	X, Z : 25 W/m-K; Y : 0.5 W/m-K
Heat generation rate	5000 W/m^3

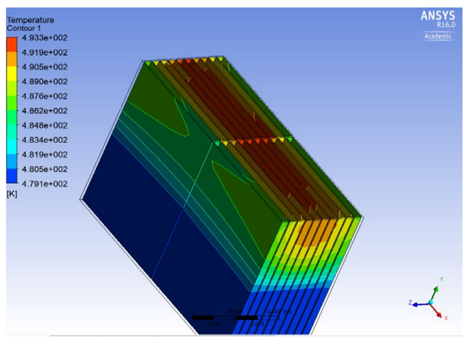

Fig. 3. Temperature distribution for the original battery enclosure without thermal management.

Thermally feasible design

New design. One possible change in design considered is to have a gap between two cells and the system being cooled by blowing air through the gap. Thus, the design of the box shown in Fig. 1 was modified as shown in Fig. 4.

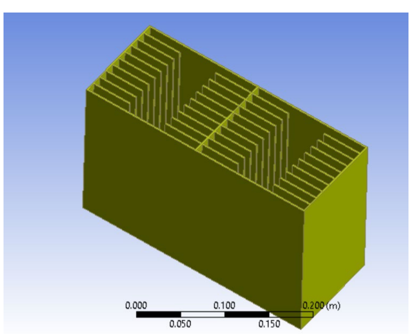

Fig. 4a. Modified battery box design.

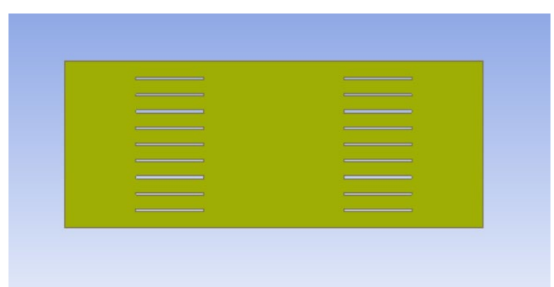

Fig 4b. Gaps for air flow.

Steady state thermal analysis of the structure in Fig. 4 (performed on a small group of 4 cells due to computation limitations) shows a maximum temperature of about 41ºC at an inlet air velocity of 1 m/s (Fig. 5). It is observed that the steady state temperature predicted by the simulation is within acceptable limits, and the air inlet speed required is also not so high as to demand huge amount of power from the battery pack.

Parametric Optimization. Based on the above, the parameters and their levels for the new design are summarized in Table 6. Considering four factors with three levels each, we have an L-9 orthogonal array. The previous analysis for the two acceleration conditions was repeated and Table 7 is populated accordingly.

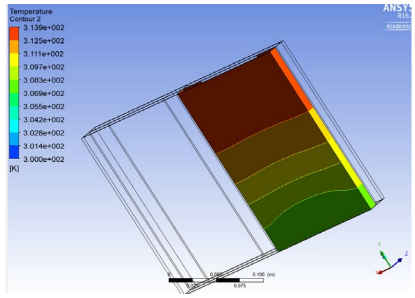

Fig. 5. Temperature profile of the cell.

Table 6. Parameters and their levels for the second optimization.

Enclosure thickness (mm)(a)	2 (1)	1 (2)	0.5 (3)
Cell gap(mm) (b)	2 (1)	1 (2)	0.5 (3)
Air flow space width(mm) (c)	50 (1)	30 (2)	10 (3)
Middle partition thickness (mm) (d)	2 (1)	1 (2)	0.5 (3)

Table 7. Mass, stress and deformation values.

Exp no.	a (mm)	b (mm)	c (mm)	d (mm)	max stress (MPa) (Z, X-accn)	max def. (mm) (Z, X-accn)	Mass (kg)
1	2	2	50	2	2.22, 2.17	0.0044, 0.0055	8.96
2	2	1	30	1	2.88, 5.1	0.0064, 0.0128	4.72
3	2	0.5	10	0.5	5.94, 10.042	0.0125, 0.032	3.183
4	1	2	30	0.5	2.58, 9.167	0.0087, 0.0349	2.45
5	1	1	10	2	2.73, 9.326	0.0087, 0.0346	2.45
6	1	0.5	50	1	2.97, 5.47	0.0092, 0.0095	3.1
7	0.5	2	10	1	3.36, 6.34	0.0078, 0.0287	2.22
8	0.5	1	50	0.5	3.63, 6.04	0.0076, 0.0078	3.8
9	0.5	0.5	30	2	3.08, 6.34	0.0078, 0.015	2.06

We find that maximum stress and deformation values are again within acceptable bounds, in fact resulting in a better performance than the original design. This shows that the new design (Fig. 4) is also structurally more robust.

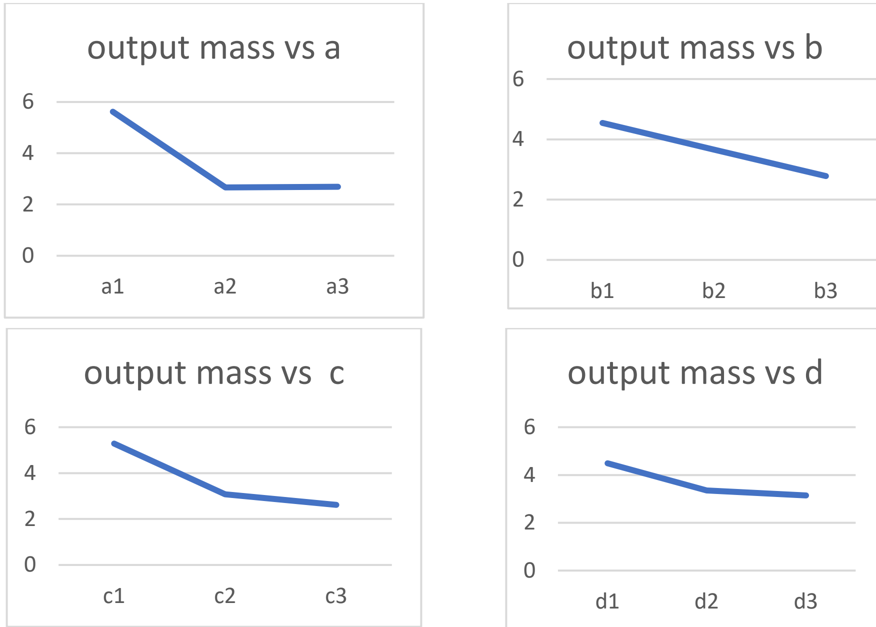

Fig. 6. Variation of mass with each parameter separately. The parameter details are indicated in Table 6.

Thermal analysis. Using the graphs (Fig. 6), we can find the optimal parameter set and hence the structurally optimal battery box design, with the least weight. Steady state thermal analysis of this design was performed with the same cell parameters as in Table 4. Again only 4 adjacent cells were simulated to reduce computational cost. This approach is expected to be valid as the significant heat flow is expected to be by the flow of air which is perpendicular to the axis of the stacked cells. It is seen that with an air inlet velocity of 5 m/s, the maximum cell temperature is around 47°C (Fig. 7). Thus, the temperature of the entire 20 X 2 pack can also be managed, with a similar air inlet between each cell. This proves that this structure is indeed feasible both with respect to mechanical integrity and thermal management.

Topology Optimization. Once the parametric optimization is complete, topology optimization can give a further weight reduction. It can be observed that the regions near the top of the enclosure wall experience little to no stresses and are hence suitable candidates for mass removal. Further removal of material gives the structure in Fig. 8, with a final weight of 1.48 kg. Since we are just removing some material from the enclosure, we do not compromise on thermal management, instead the cells near the edge will be cooler than before as they are also exposed to natural convection from the sides where material has been removed.

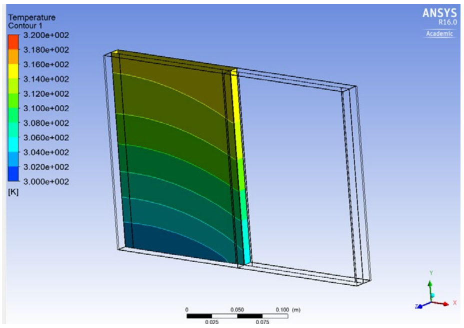

Fig. 7: Temperature profile of the cell in the final optimized structure

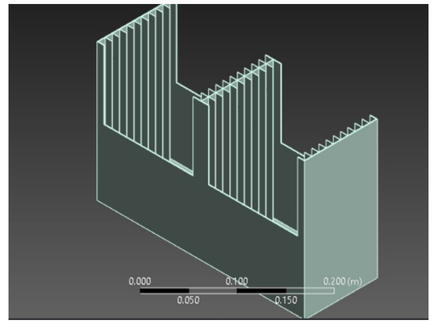

Fig. 8: Structure after topology and parametric optimization

Stress Analysis. Structural simulations were performed on this structure and maximum stresses and deformations on the battery enclosure are found to be within acceptable bounds, as shown in Fig. 9. The stresses on the individual cells are also found to be negligible, as shown in Fig. 10. Cells and enclosure are part of the same simulation, with the cells hidden in Fig. 9 and the enclosure and other cells hidden in Fig. 10.

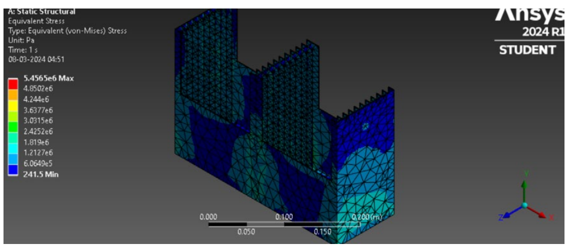

Fig. 9a. Stress dist.in final struct. for Z accel.

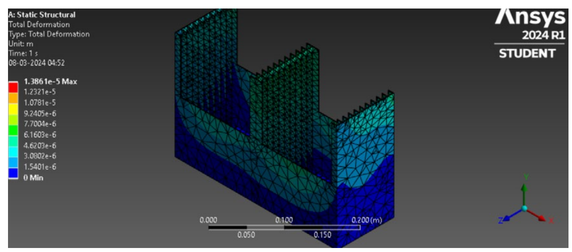

Fig. 9b. Deformation distribution for Z accel.

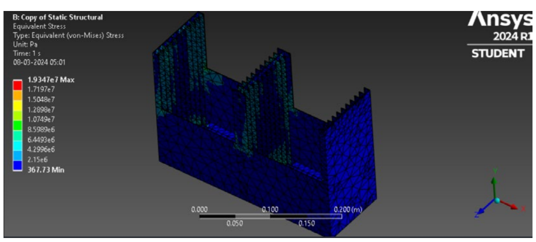

Fig. 9c. Stress distribution for X accel.

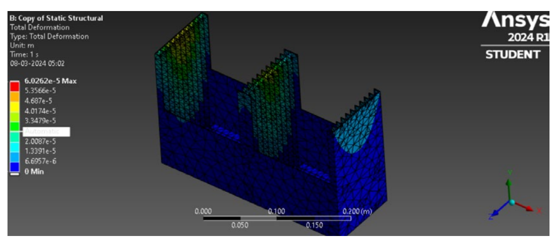

Fig. 9d. Deformation distribution for Z accel.

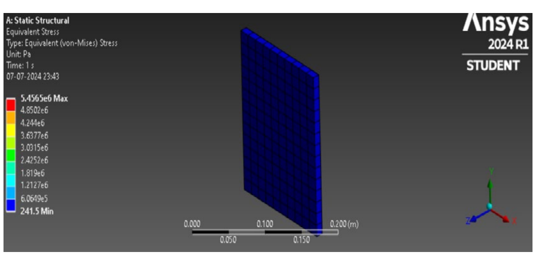

Fig. 10a. Stress Dist. for a cell, Z accel.

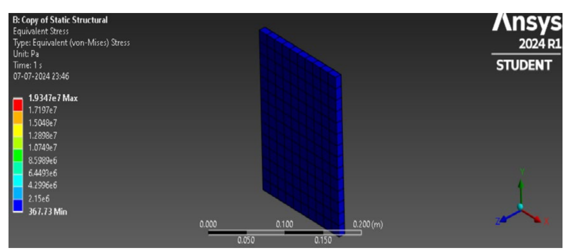

Fig. 10b. Stress Dist. for a cell, X accel.

Materials Research Proceedings 44 (2024) 465-474 https://doi.org/10.21741/9781644903254-50

Mode	Frequency (Hz)
1	359.94
2	374.4
3	391.94
4	614.67
5	691.11

Table 8. Frequency modes of battery box.

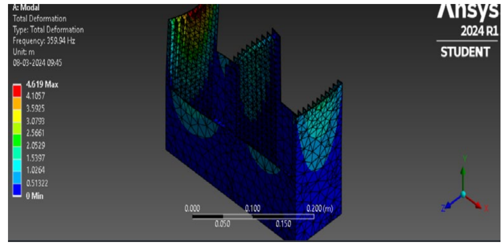

Fig. 11. First frequency mode

Modal Analysis. Another important aspect of structural design is modal analysis. The battery box and cells will be exposed to vibrations as the vehicle moves on the ground. The frequency modes of the battery box should be higher than the normal frequencies of vibration during the vehicle's motion to avoid resonance. Based on previous reports, we want the frequency modes to be higher than ~ 80 Hz [14]. The first 5 frequency modes for the battery box are tabulated in Table 8, and we find that the modes are much higher than the lower frequencies encountered during driving.

Conclusions and Future work

The given battery enclosure structure was optimized, to make it lightweight and at the same time able to resist forces during braking, acceleration and turning. The structure was also shown to be thermally feasible and temperature of the cells during steady state was found to be within their functional range. In all the simulations, the stresses on the cells were negligible, ensuring that the cells were not damaged. In the process, weight reduction from 7.67 kg to 1.48 kg was achieved, a reduction by almost 80%. Thus, significant reduction in weight could be achieved by first identifying and optimizing relevant parameters of the structure and later by topology optimization. The model above can be made more realistic by considering the exact properties of different parts of the pouch cells (electrodes, electrolyte, etc.), instead of volume averaged properties, as used here. The cells are assumed to be nearly rigid, thus can be constrained by two short separators (Fig. 8). A more realistic model will encompass the non-rigidity of the cell. The boundary conditions of the battery enclosure can also be modified to nuts/bolts at specific locations, instead of fixed joints along the entire edge. The methodology presented in this paper can be used as per the system under consideration to make the system lightweight and reliable. Further lightweighting of battery packs is proposed to be attempted in the future by material substitution for some or all portions.

References

[1] Y. Chen, G Liu, Z.Y. Zhang, S.J. Hou, Integrated design technique for materials and structures of vehicle body under crash safety considerations, Struct. Multidiscip. O. 56 (2017) 455. https://doi.org/10.1007/s00158-017-1674-8

[2] L. Chen, X.Y. Zhao, Proc. 2019 Int. Conf. Robotics, Intelligent Control and Artificial intelligence, Association for Computing Machinery, Shanghai, China.

[3] Y. Pan, Y. Xiong, L. Wu, K. Diao, W. Guo, Lightweight Design of an Automotive Battery-Pack Enclosure via Advanced High-Strength Steels and Size Optimization, Int. J. Automot. Tech. 22 (2021) 1279. https://doi.org/10.1007/s12239-021-0112-5

[4] Q.-S. Chen, H. Zhao, L.-X. Kong, K.-W. Chen, Research on Battery Box Lightweight Based on Material Replacement, Adv. Eng. Res. 141 (2017) 346. Proc. of 5th Int. Conf. on Mechatronics, Materials, Chemistry and Computer Engg (ICMMCCE 2017). https://doi.org/10.2991/icmmcce-17.2017.72

[5] X. Chen, M. Li, S. Li, J. Jin, C. Zhang, Machine and Deep Learning for Digital Twin Networks: A Survey, Society of Automotive Engineers (SAE)-China Cong., Singapore. https://doi.org/10.1109/JIOT.2024.3416733

[6] K.K. Parsons, T.J. Mackin, Design and Simulation of Passive Thermal Management System for Lithium-Ion Battery Packs on an Unmanned Ground Vehicle, J. Therm. Sci. Eng. Appl. 9 (2017) 011012. https://doi.org/10.1115/1.4034904

[7] H. Sun, R. Dixon, Development of cooling strategy for an air cooled lithium-ion battery pack, J. Power Source. 272 (2014) 404-414. https://doi.org/10.1016/j.jpowsour.2014.08.107

[8] J. Lian, M. Koch, W. Li, T. Wierzbicki, J. Zhu, Mechanical Deformation of Lithium-Ion Pouch Cells under in-plane Loads—Part II: Computational Modeling, J. Electrochem. Soc. 167 (2020) 090556. https://doi.org/10.1149/1945-7111/ab9eee

[9] L. Cheng, A. Garg, A.K. Jishnu, L. Gao, Surrogate based multi-objective design optimization of lithium-ion battery air-cooled system in electric vehicles, J. Energy Stor. 31 (2020) 101645. https://doi.org/10.1016/j.est.2020.101645

[10] Ranjit Roy, A Primer on the Taguchi Method, Society of Manufacturing Engineers, ISBN 13: 978-0-87263-864-8

[11] https://www.me.psu.edu/cimbala/me345/Lectures/Taguchi_orthogonal_arrays.pdf

[12] D. Agwu Daberechi, F.K. Opara, N. Chukwuchekwa, D.O. Dike, L. Uzoechi, 2017 IEEE 3rd Int. Conf. on Electro-Tech. for Nat. Dev. (NIGERCON)

[13] G. Vertiz, M. Oyarbide, H. Macicior, O. Miguel, I. Cantero, P. Fernandez de Arroiabe, I. Ulacia, Thermal characterization of large size lithium-ion pouch cell based on 1d electro-thermal model, J. Power Source. 272 (2014) 476. https://doi.org/10.1016/j.jpowsour.2014.08.092

[14] M. Hartmann, M. Roschitz, Z. Khalil, Enhanced Battery Pack for Electric Vehicle: Noise Reduction and Increased Stiffness, Mater. Sci. Forum 765 (2013) 818. https://doi.org/10.4028/www.scientific.net/MSF.765.818