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Numerical Analysis of Structural Batteries Response with the Presence of Uncertainty

Syahiir Kamil[a], Mohamad Syazwan Zafwan Mohamad Suffian[b], Ahmad Kamal Ariffin[a] & Abdul Hadi Azman[a]

[a]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor,Malaysia*

[b]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia*

**Corresponding author: sharkilspot@gmail.com*

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ABSTRACT

In order to further reduce oil dependence and world pollution, there's growing interest in embedding batteries such as Li-Po batteries within vehicle components. The implementation of structural batteries is believed to be the next promising approach for next-generation hybrid and electric vehicles. The proposed research is devoted to the uncertainty analysis of structural battery behavior under various parameters. To help with the analysis, a dedicated algorithm based on an elimination approach to solve numerical problems with uncertain parameters is successfully developed using Visual Basic. The Constant Strain Triangle element with linear elastic behavior is used as a structural model to simplify the model. Uncertainty of the material properties and loading are modeled as Fuzzy Random Variables. In evaluating the influence of the uncertainty parameters, Interval Monte Carlo Simulation and the interval finite element method are used to compute the bounds of the structure behavior. Simulation results between the Interval Monte Carlo and Deterministic are compared to evaluate the significance of the uncertainty factor influences. It is shown that the structural batteries that can be considered safe based on deterministic parameters may be unsafe if the uncertainty parameters are considered. The proposed approach could detect the results that are not necessarily detected through deterministic means. By producing a broader result, further prevention and consideration can be made to avoid catastrophic events.

Keywords: Electric vehicle; fuzzy random variable; Interval Monte Carlo; structural battery; uncertainty

INTRODUCTION

To reduce the world's reliance on oil for transportation and CO_2 emissions related to transportation, alternative vehicle technologies such as electric vehicles (EVs) are being developed. The world's reliance on fossil fuels and the resulting emission of greenhouse gases could be significantly reduced by encouraging the use of EVs and renewable energy sources (Richardson 2013). The automotive sector is looking into new strategies to increase energy efficiency and lower greenhouse gas emissions from cars, trucks, buses, and other road vehicles. One approach is to replace vehicle components (such as the body panels and chassis) with structural batteries, which serve multiple functions such as load bearing, energy storage, and space-saving. (Pattarakunnan et al. 2021).

However, there are always dangers connected to battery technology that put people's safety in jeopardy. The lithium-ion battery's short circuit phenomenon may result in thermal runaway, and it can cause irreversible battery damage (Sheikh et al. 2021). Although various types of loading conditions that can cause failure or damage to the structural batteries have been studied (Galos et al. 2020).

It is unknown how big the influence of the uncertainty factor that appears on the structural batteries can lead to. In the case of EVs susceptible to various loading in the environment, deterministic analysis is insufficient. It is necessary to consider the uncertain nature of the material properties and the environmental loading conditions (Troian 2021).

Practical engineering issues involve many uncertainties. Two main categories of uncertainty can be distinguished: aleatory and epistemic. Both probabilistic and non-probabilistic methods can be used to approach this uncertainty (Yusmye 2022). In this study, the structural batteries that can be found on EVs are examined. The structure consists of skin, core, and embedded pouch Li-Po batteries. Numerical uncertainty analysis is conducted through the developed Interval Monte Carlo approach with the presence of uncertainty.

METHODOLOGY

STRUCTURAL BATTERIES

Structural batteries are integrated into composite materials to produce lightweight energy storage components with high mechanical properties and high energy storage capacity (Galos et al. 2020). It can be created by removing some fiber reinforcement to make room for the batteries. However, this procedure will reduce the failure stress, stiffness, and other mechanical properties of the laminate material. The load-bearing face sheets can remain unaffected by using an alternative strategy in which the batteries are embedded inside the core of sandwich composites (Kwon & Nam 2021).

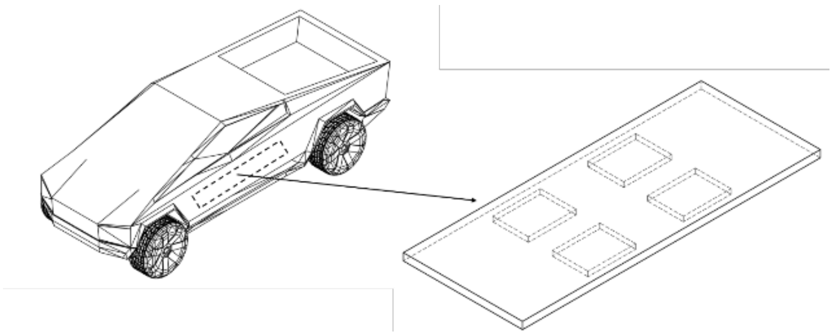

FIGURE 1. Electric Vehicle with Embedded Batteries within Vehicle Component

The modeled laminates are made from a composite material of thin Carbon Fiber Reinforced Polymers (CFRP) face skins and PVC Foam cores. Part of the structure is taken as Representative Elementary Volume (RVE) to be analyzed. The RVE is 200 mm long, 30 mm wide, and 6 mm thick. The embedded LiPo batteries are 40 mm long, 30 mm wide, and 4 mm thick (Keshavarzi et al. 2022). Two batteries are arranged in series with a 40 mm separation between them. Figure 1 and Figure 2 show the arrangement of the batteries in the core. The properties of the CFRP face sheet, PVC Foam core, and LiPo battery are provided in Table 1.

TABLE 1. Properties of the constituent materials in RVE

Material Parameter	CFRP (Ladani et al. 2016)	PVC Foam (Daniel et al. 2009)	LiPo Battery (Arief Budiman et al. 2022)
	45 GPa	95 GPa	150 MPa
	0.33	0.33	0.3
Geometry Parameter			
Length, Width, Thickness	200, 30, 0.5 mm	200, 30, 5 mm	40, 30, 4 mm

The source of the applied force to the structural batteries is assumed to be from the incoming projectile, as illustrated in Figure 3. The projectile, such as debris on the road, can cause an impact load on the structure. The load and reaction force that can happen can vary depending on the uncertain projectile mass, velocity, and debris material properties. The angle of the incoming projectile is also uncertain. Different angles will lead to a different magnitude of the applied load. The excessive response to mechanical abuse could lead to life-threatening events such as thermal failure on the embedded batteries.

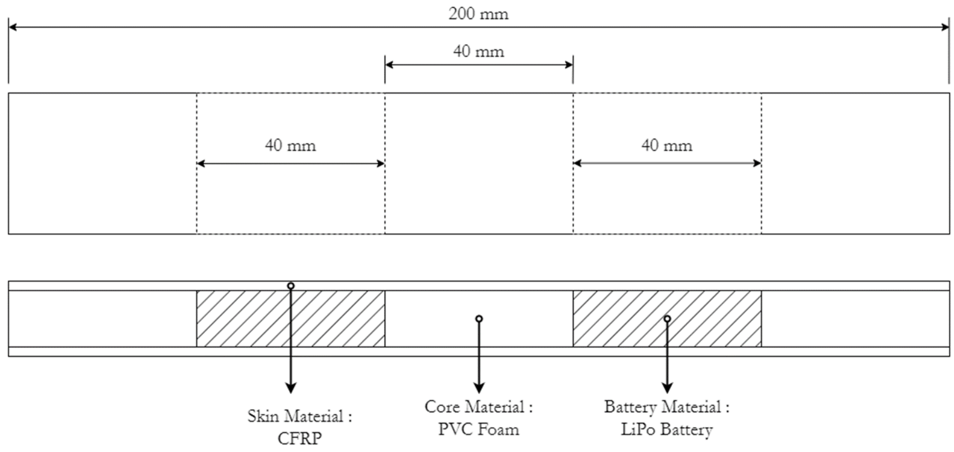

FIGURE 2. Arrangement of the Batteries in the Core and its Dimension

NUMERICAL MODELLING

In this study case, through a developed algorithm in Visual Basic, numerical simulation with Constant Strain Triangle (CST) elements are implemented with linear elastic behavior. The study scope is limited to two-dimensional (2D), and the nonlinearities are ignored. The generalized Hooke's law provides the stress-strain relations for linear elastic materials. Through simulation, it is possible to determine the response of complex materials such as composite materials (Khalid et al. 2022). The parameters that being studied are consist of deterministic and uncertainty values.

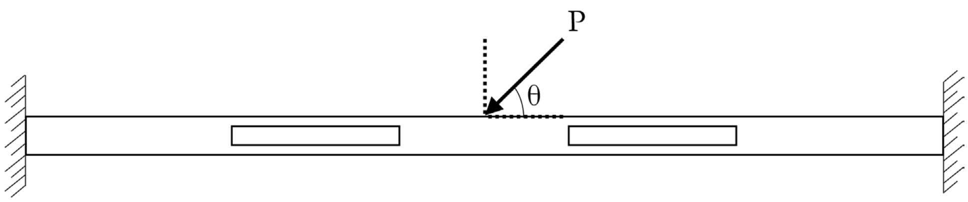

FIGURE 3. Case Studies Schematic

IMPACT LOAD FACTORS FOR STATIC ANALYSIS

As we are aware, an incoming projectile has mass and velocity, when it collides with an object, it will produce an impact load (P). In order to simplify the analysis, rather than conducting a dynamic analysis, an amplified static analysis is used. For a static stress analysis to accurately predict the maximum deflection and stress dynamically, the static force must be multiplied by an impact factor. (Riera 1993).

$$F_e = W\left(1 + \sqrt{1 + \frac{V^2}{g\delta_{st}}}\right) \tag{1}$$

UNCERTAINTY – FUZZY AND RANDOM

In real engineering cases, there could be numerous sources of uncertainty. Therefore, deterministic models may not be sufficient to analyze the response of structural response (Troian 2021). There are two main categories of uncertainty: aleatory and epistemic. While epistemic uncertainty is knowledge-based, it is caused by flawed modeling, oversimplification, and a lack of readily available databases. For this type of uncertainty, the uncertainty can be based on expert opinion (Yacob et al. 2019). As for aleatory uncertainty, it is caused by natural variability and is typically modeled by random variables (Jahani et al. 2014). Various factors could contribute to this aleatory uncertainty, such as manufacturing procedure in the composite materials (Khalid et al. 2023). For the study case, load and material properties are considered uncertain. Load magnitude and angle are modeled as fuzzy variables, while material properties are modeled as random variables, as shown in Figure 4.

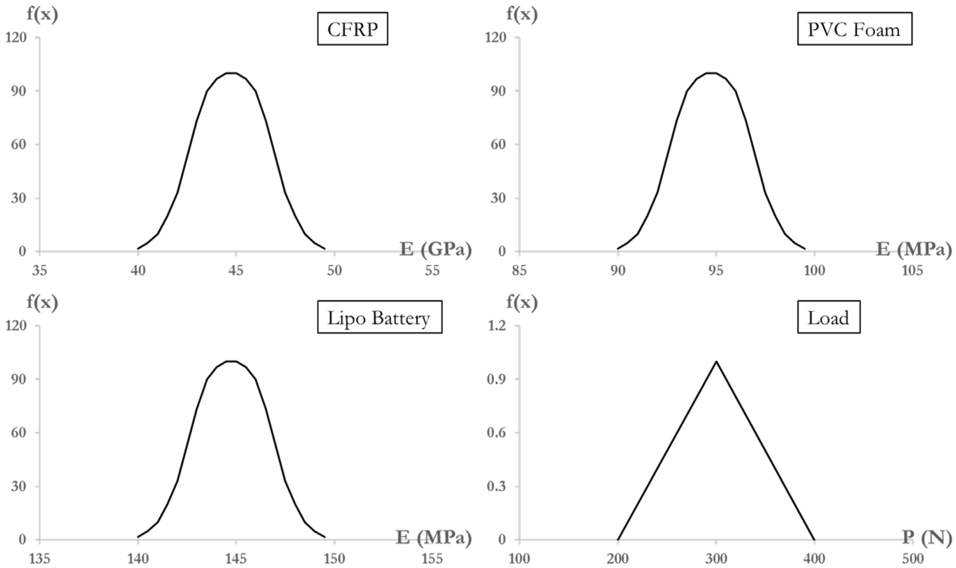

FIGURE 4. Membership Functions of Distribution Parameters

VALIDATION

The need for an easy numerical method is evident because finding a model with appropriate representation for many real-world situations with an exact solution is difficult. However, the confidence in the validity of results from approximate methods must be gained. The approach must be used initially in configurations where precise or well-established solutions are available. The deflection formula from a simple beam case is used for validating the skin, core and battery model. By comparing the result from the numerical method and the analytical method, relative error (RE) is determined.

$$\Delta_{max} \text{ (at centre)} = \frac{PL^3}{192\ EI} \tag{2}$$

$$RE = \left| \frac{\Delta_{max}\left(x=\frac{L}{2}\right) - \Delta(\text{max})\ (\text{node at centre})}{\Delta_{max}\left(x=\frac{L}{2}\right)} \right| \tag{3}$$

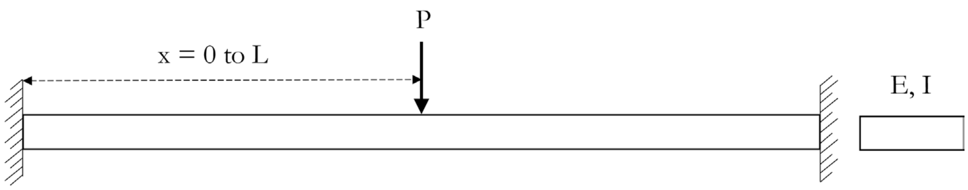

FIGURE 5. Fixed Both Ends Beam - Point Load at Centre

DETERMINISTIC FINITE ELEMENT (DFE)

The deterministic analysis treats the load and material properties as constant values. After the initial nodal coordinate, element connection, load, and boundary conditions are recorded, by combining each local stiffness matrix of the CST element into the global stiffness matrix. The overall matrix is solved through the gauss elimination method. Lastly, for each element, using element connectivity, the element displacement vector is extracted, and element stresses are determined. The mesh-generation scheme suggested by (Zienkiewicz & Phillips 1971) is implemented for generating element connectivity and nodal-coordinate data.

INTERVAL MONTE CARLO FINITE ELEMENT (IMCFE)

In uncertainty analysis, to compute the fuzzy variables, the α-cut approach is used (Yusmye, 2022). As for random variables, the Mersenne Twister algorithm MT19937 generates random numbers (Mohamad Suffian et al. 2022). Both aleatory and epistemic uncertain inputs will be processed in the IMCFE to generate results in the upper- and lower-bound (Figueroa-Garcia et al. 2019).

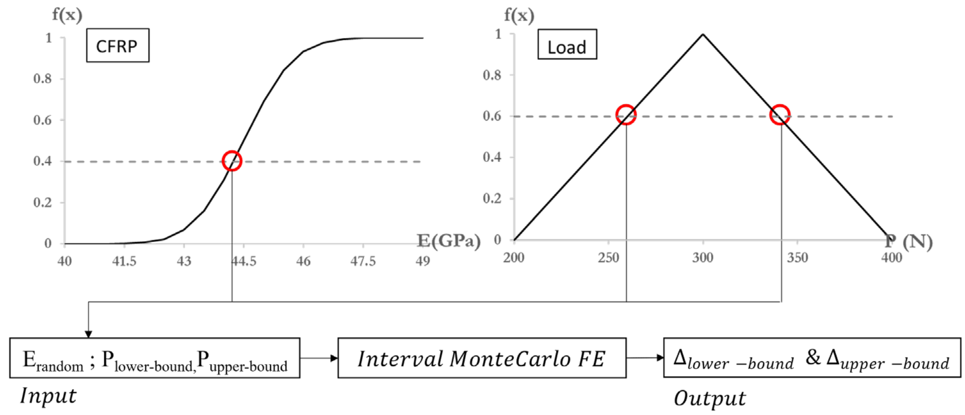

FIGURE 6. Interval Sampling in IMCFE to Calculate the Bounds

Referring to Figure 6, the uncertainty parameter with a random and fuzzy value will be processed simultaneously with each simulation iteration. The MT19937 algorithm and specified formula generates a random parameter for the random value. As for the fuzzy value, at the specified membership of α, the interval value of upper- and lower-bound as fuzzy parameters will be generated. All these parameters is fed into IMCFE as input parameters.

Each iteration produce unique output depending on the generated random number and the α membership that has been chosen. The more α membership and iteration numbers chosen, the more accurate the result will be. If the iteration number is insufficient, the extreme results might not be predicted. Although it depends on the number of the random input parameter, a sample number of 10^6 is usually sufficient.

With the combination of interval input and random input fed into the solver, IMCFE produce a result in the form of an interval with random bounds. With sufficient iteration, representative interval results that accurately predict the response will be produced. Due to some input parameters being considered as fuzzy values, the iterations requirement is further reduced.

Additionally, the bound vary because some of the inputs are random values. These are considered the advantages of IMCFE compared to the regular Monte Carlo or Fuzzy finite element method.

RESULTS AND DISCUSSION

The numerical procedure starts with determining the ideal mesh number for each constituent material in RVE. After the validation process, DFE and IMCFE on each material are performed. Finally, the whole RVE is numerically analyzed with the presence of uncertainty.

MESH CONVERGENCE

In order to avoid getting erroneous analysis, results obtained from the simulation need to be validated first. Generally, the finer the mesh, the more accurate the result. However, it also comes with an increase in computational time. An ideal mesh consists of just enough mesh numbers while maintaining accurate results.

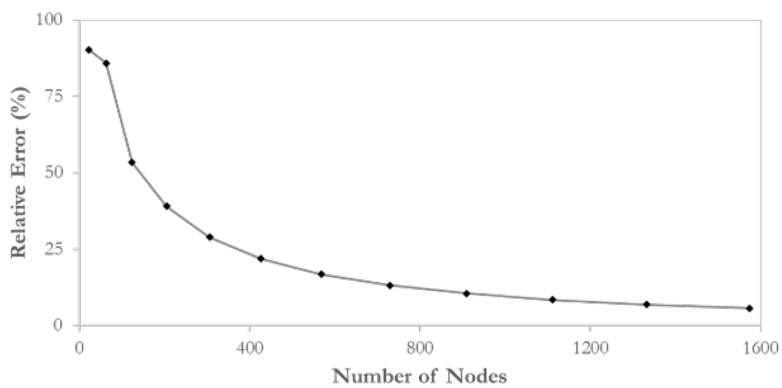

FIGURE 7. RE With Increasing Number of Nodes (NON) on Skin

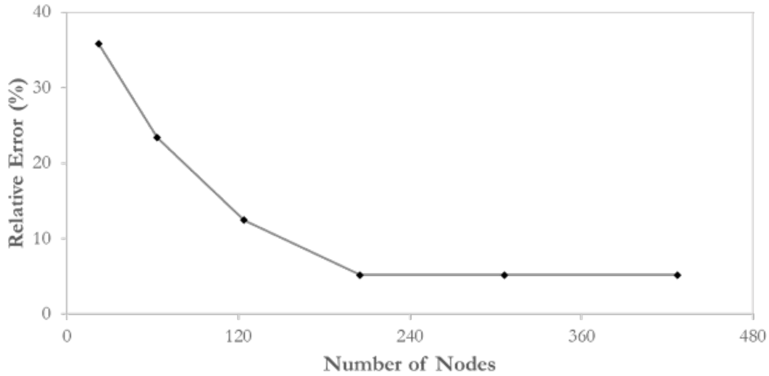

FIGURE 8. RE With Increasing NON on Core

As illustrated in Figure 7, the skin material starts converging with 700 NON, while in Figure 8, the core material reaches its ideal number with only 400 NON. This is due to the geometrical factor of the skin. The skin that only has a thickness of 0.5 mm bends more significantly than the core material that has a 5 mm thickness. The model that used the CST elements are known to produce a stiffer model. It also converges very slowly compared to the regular beam element. The reason being stress varies linearly through the depth of the beam. However, when applying a bending load, CST predicts constant stress within each element.

It can be observed from skin convergence in Figure 7 (NON = 100) that, the increase in the number of nodes does not generate equal better RE. This is because the increase of mesh element number along the length of the beam is not representative enough. Instead, it needs more row mesh elements along the depth of the beam to simulate an actual beam that flexure. It can be concluded that total NON is not immediately the only influence factor in the convergence, but the location of the mesh concentration also needs to be considered.

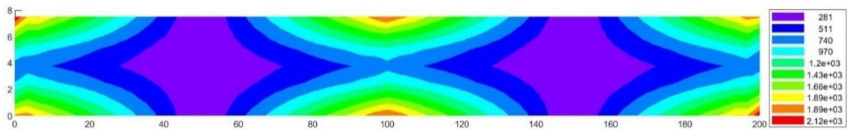

FIGURE 9. Von Mises Stress Contour of Skin Material

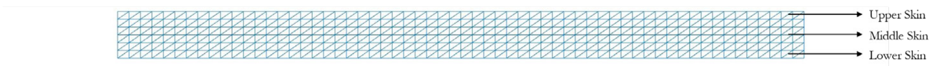

FIGURE 10. Mesh Grid of Skin Material

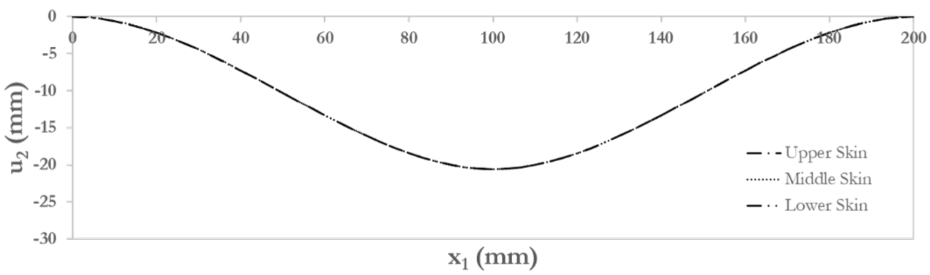

FIGURE 11. Deterministic Axial Displacement of Various Layers on Skin Material

DFE OF SKIN, CORE, AND STRUCTURE

The simulated model of skin, core, and sandwich material response to the constant load and deterministic material properties are evaluated through DFE. Figure 9, Figure 10, and Figure 11 illustrate the von Mises stress distribution, mesh grid, and displacement response chronologically. In the simulated model, as seen in Figure 10, the skin model consists of three layers; upper, middle, and lower skin layer. If reviewed on each layer of skin material, all three have roughly the same displacement, which is 20 mm as shown in Figure 11. The whole layer of the skin deforms uniformly with maximum von Mises stress of 2087 MPa located at the middle and the fixed end, as seen in Figure 9.

For the core material, Figure 12, Figure 13, and Figure 14 illustrate the von Mises stress distribution, mesh grid, and displacement response chronologically. In the simulated model, as seen in Figure 13, the core model also consists of three layers; upper, middle, and lower, similar with the skin layer. The core experiences similar deformation on all three layers, similar with the skin material but with a much bigger magnitude of 110 mm, as shown in Figure 14. The contour of the von Mises stress on the core material behaves similarly to skin material with maximum von Mises stress of 200 MPa located in the middle, as seen in Figure 12.

In theory, the increase in thickness of a plate, the harder it is to bend the plate. Although the core is thicker than the skin, the core has lower Young's modulus properties than the skin. Comparing Figure 9 and Figure 12, it is shown that the core deforms 60% more and experiences 11% lower mechanical loading, meaning the core is stiffer than the skin. As such, the combination of the two skins on each surface of the core creates a material that has tough skin but also has the advantages of a lightweight core while maintaining adequate stiffness. Combining the skin and core produce a new material called sandwich structure.

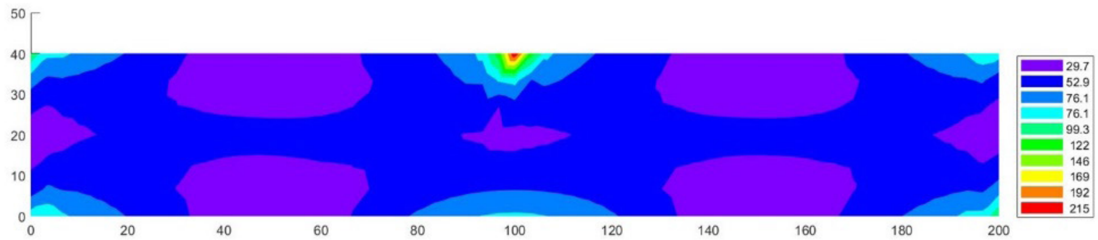

FIGURE 12. Von Mises Stress Contour of Core Material

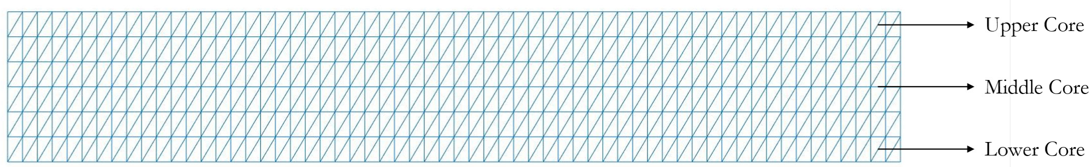

FIGURE 13. Mesh Grid of Core Material

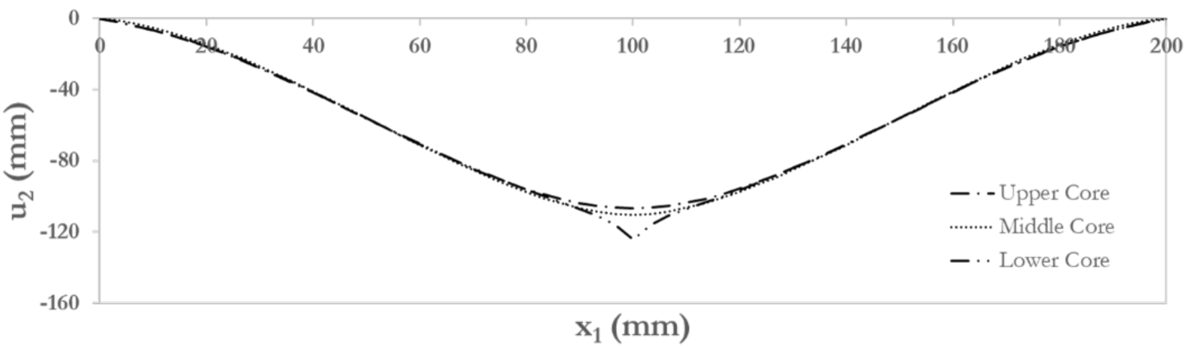

FIGURE 14. Deterministic Axial Displacement of Various Layers on Core Material

The layers deform a bit differently in the sandwich structure with the same applied load. The layer on the sandwich structure consists of upper skin, core, and lower skin can be seen in Figure 16. The biggest is the deformation of the upper layer of the upper skin with a magnitude of 9 mm, followed by the middle layer of the middle core by 7 mm, and finally, the lower layer of the lower skin by 5 mm, as shown in Figure 17. Combining the two skins into the core significantly reduces the layers' deformation. It has a 55% reduction on the skin and a 93% improvement on the core compared to the combined structure.

In response to the combining the whole material, von Mises stress is reduced by 47% compared to the skin material only with magnitude of 1115 MPa located at the middle of the upper skin, as seen in Figure 15. By examining the stress contour, it can be said that the stress is concentrated in the skin, implying that the skin mostly bears the mechanical loading, while the core functions as a stiffener to the whole structure. This concludes the simulation of sandwich structure with deterministic value.

Referring to Figure 2, the Li-Po battery can be found inside the core of the structural batteries. Previous works of literature (Goodman et al. 2020; Luo et al. 2017; Zhu et al. 2016) stated that there is maximum allowable deformation on the batteries before internal short circuit occur. This phenomenon could lead to a life-threatening event due to thermal runaways. Specifically for Li-Po batteries, 7 mm is the maximum deformation it can sustain before it experiences a short circuit. Without considering uncertainty, the flexure in the sandwich structure's core is still considered safe.

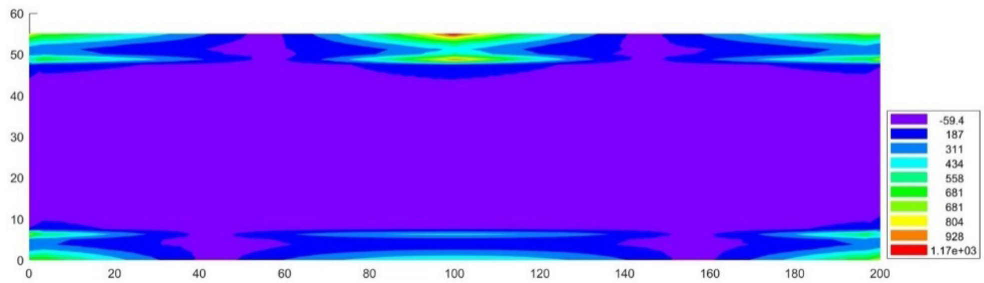

FIGURE 15. Von Mises Stress Contour of Sandwich Material

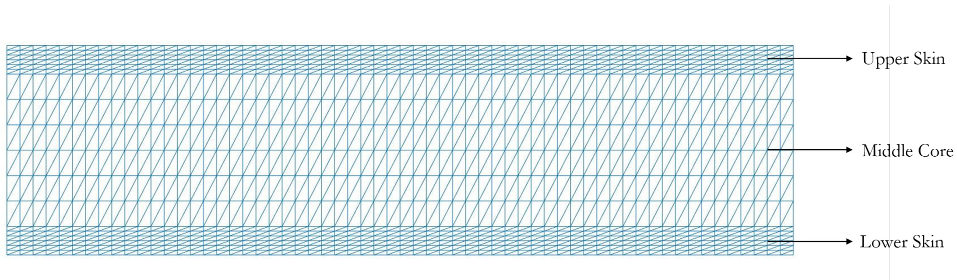

FIGURE 16. Mesh Grid of Structural Batteries

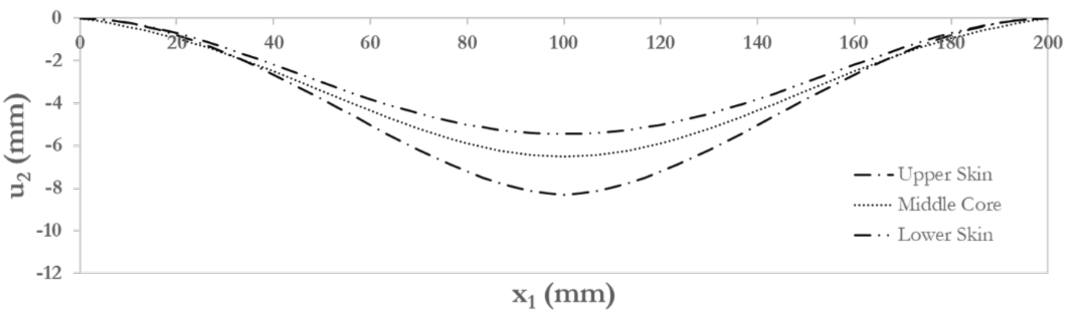

FIGURE 17. Deterministic Axial Displacement of Various Layers on Structural Batteries

IMCFE OF SKIN, CORE, AND STRUCTURE

Even though the sandwich structure appear to be safe with the deterministic analysis, the uncertainty factor must be considered. The response of the skin, core, and structural batteries is evaluated by considering the presence of uncertainty on the load and material properties. Through IMCFE, the simulation results yield lower- and upper-bound interval results. With the availability of these intervals, more refined and accurate analysis and conclusion will be able to be drawn due to the ability of the simulation in producing broader possible results.

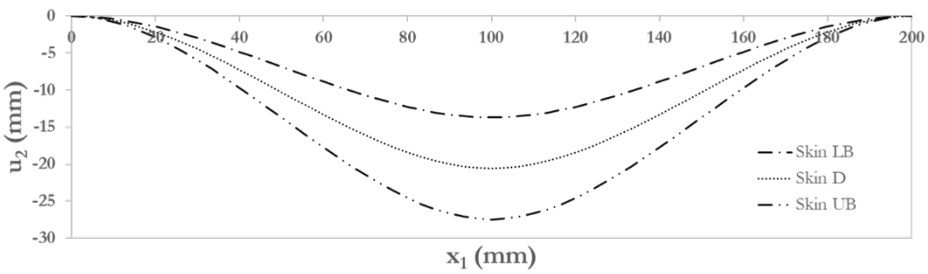

FIGURE 18. Uncertainty Response of Various Layers on Skin Material

With the presence of uncertainty, the simulation of the skin model is compared with deterministic analysis. From Figure 18, ranging deformation of 12 mm to 27 mm is predicted with the specified uncertainty variable input. Similar to DFE, IMCFE also predicted similar deformation curves on the upper, middle, and lower layers of the upper skin. With a difference of almost 7 mm from the DFE on each layer, the total difference in the bending deformation could become 15 mm which is 75% of the mean value. It is quite extensive and could have a considerable impact.

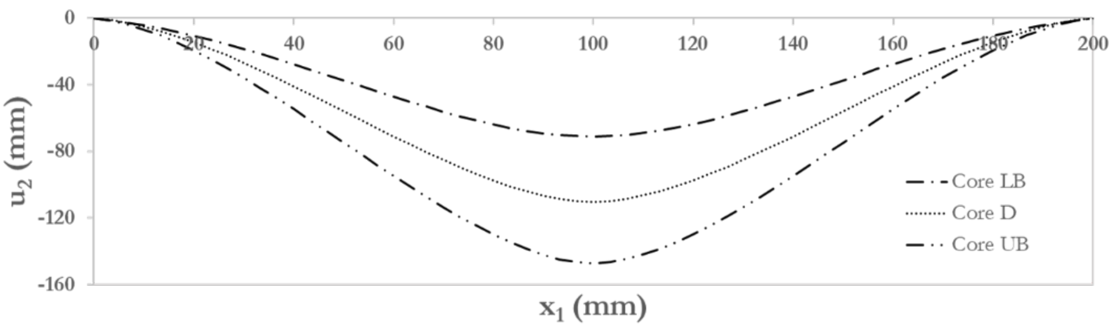

FIGURE 19. Uncertainty Response of Various Layers on Core Material

In the case of core deformation, Figure 19 illustrates that lower-bound deformation of 70 mm and upper-bound of 150 mm is found if the uncertainty is considered. In IMCF, the core also experiences a similar displacement curve across all layers, similar with in DFE. The 40 mm displacement diversity on each layer can produce a total deviance of 80 mm which is 67% higher from the deterministically predicted value.

For the whole structural batteries, similar to DFE, there's a discrepancy in the deformation range on all the layers. Referring to Figure 20, the biggest interval was found on the middle core with a magnitude of 7 mm, followed by upper skin by 6 mm and finally, lower skin by 4 mm. The biggest flexural deformation as 11 mm found on the lower layer of the upper skin which yields 83% of the mean value.

Figure 20 shows that the core in the sandwich structure experience interval deformation between 3 mm and 11 mm with a deterministic value of 6 mm. According to (Luo et al. 2017), maximum deformation of 7 mm is allowed for Li-Po batteries before a short circuit occurs. If only deterministic analysis were considered, the maximum deformation of 6 mm would occur, which is still under the 7 mm threshold.

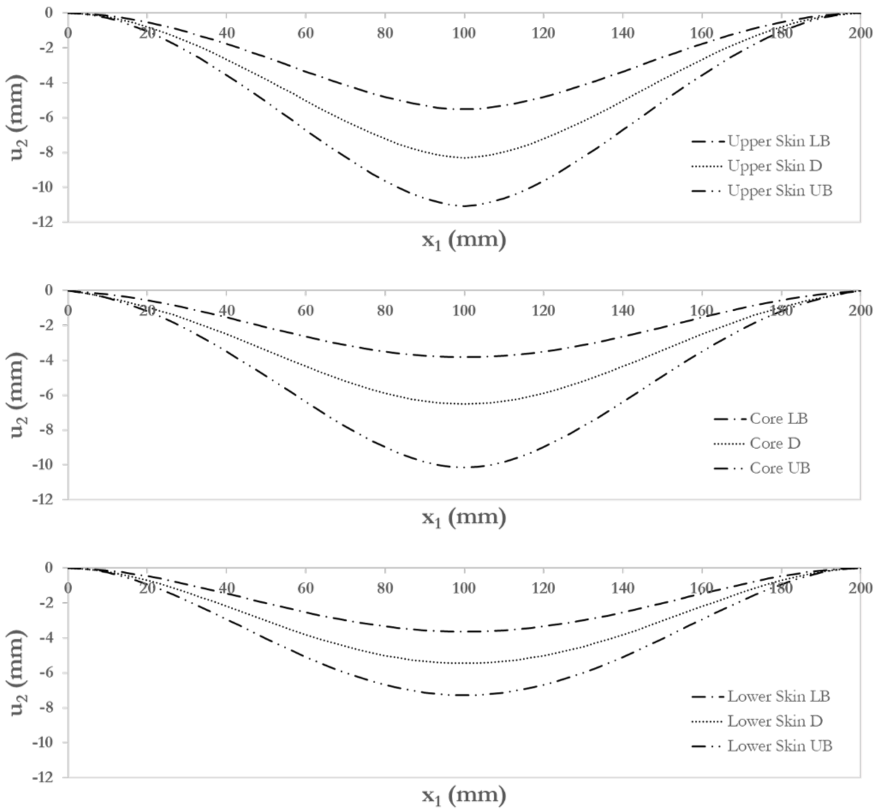

FIGURE 20. Uncertainty Response of Various Layers on Structural Batteries

The structural batteries appear to be safe without the consideration of uncertainty. However, it is not the case if the presence of uncertainties is included in the analysis. In Figure 21, the dashed area illustrates the event where a short circuit would happen. When the deformation that occurred exceeds 7 mm, the short circuit can lead to thermal runaway and life-threatening accidents.

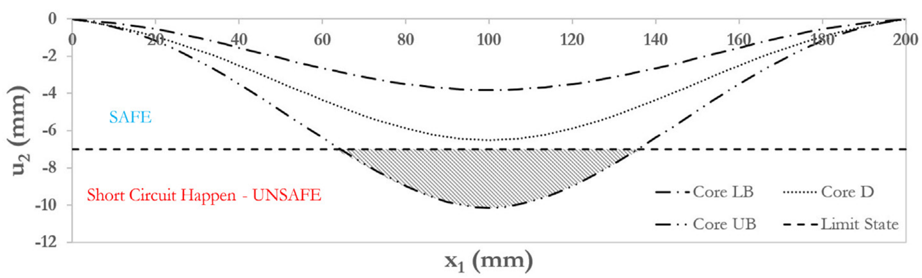

FIGURE 21. Limit State of Structural Battery from Short Circuit

CONCLUSION

Uncertainty variables consist of fuzzy variables and random variables found on structural batteries are simulated numerically through developed IMCFE. Considering the presence of uncertainty, the simulation results yield an interval result consisting of lower- and upper-bound values. With the availability of these intervals, more refined and accurate analysis and conclusion can be drawn because the simulation can produce broader possible results. Results that are not necessarily detected through deterministic means could be detected through this approach. Further prevention and consideration can be made to avoid catastrophic events.

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DECLARATION OF COMPETING INTEREST

None

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