A DETERMINISTIC DIGITAL TWIN-BASED METHOD FOR DAMAGE DETECTION OF COMPOSITES SUBJECTED TO IMPACT LOADING: DEVELOPMENT AND VALIDATION

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Abstract: *Both monolithic and sandwich composites are highly susceptible to impact loading. Despite of their inherent strength-to-weight ratio benefits, this vulnerability constitutes a major concern related to structural integrity. Although structures designed with fail-safe principles can withstand in theory partial system failure, the early detection of in-service damage is useful for supplementing regular inspections. The development and validation of a time-efficient predictive method for the localization and quantification of damage to composites can bring numerous benefits such as rapid post-damage strength estimation. In the current study, a deterministic digital twin-based algorithm for the damage localization and quantification of a composite sandwich panel subjected to soft body impact is developed. The effectiveness and robustness of developed algorithm is highlighted, whilst proposals for enhancement of time-efficiency of algorithm are provided.*

Keywords: Multi-Fidelity Modeling; Impact Simulation; Structural Health Monitoring; Composites; Fibre Bragg Gratings.

1. Introduction

The constant requirement of aerospace industry to enhance the structural efficiency has driven to the usage of high-performance composite materials, either monolithic or sandwich. However, aerospace composite structures are prone to damage due to high-velocity impact events such as bird strike, hail impact, etc. These impact events can result in extensive damage including structure perforation, which will eventually degrade its post-impact residual strength. Therefore, the early detection of damage in composite structures is imperative to avoid catastrophic failure. The development and validation of a time-efficient predictive method for the localization and quantification of damage to composites can bring numerous benefits such as rapid post-damage strength estimation; however, the detection and estimation of composites damage using digital twin (DT) technology is a brand-new technique that has not been widely used in aerospace industry yet.

A few attempts for the integration of digital twin concept to aerospace and space industry are shown below. Tuegel et al. [1] presented a conceptual model using digital twin to predict the aircraft structural life prediction and to assure the structural integrity in flight conditions. Later, in 2012, Glaessgen and Stargel [2] proposed a digital twin paradigm for the prediction of the health and the remaining life of future NASA and U.S air force vehicles. Despite all of that, the digital twin technology is not mature enough for use in the aerospace industry and more development is required in several sectors such as data transmission, collection and processing, communication-interaction technology, modeling-simulation technology and sensing-measurement technology. The modeling technology is the main research focus of this study, nevertheless important conclusions can be extracted for the data recording device (interrogator) and the FBG sensing technology.

In the current study, a deterministic digital twin-based algorithm for the damage localization and quantification (named Damage Evaluation Algorithm-DEA) of a composite sandwich panel subjected to soft body impact is developed. The principle of its operation is based on the comparison of the strain histories recorded by FBG sensors with the numerically calculated ones. More specifically, high-fidelity (HF) and low-fidelity (LF) finite element (FE) models are employed as digital replicas of actual structure; firstly, the low-fidelity model is used as a computationally efficient tool for the identification of impact loading conditions and damage localization based on strain measurements recorded by the FBG sensors, and afterwards the high-fidelity model is employed for damage quantification considering known the position and load-time profile. For the better comprehension of general idea, a schematic of digital-twin-assisted damage diagnosis concept including the function of developed models is shown in figure 1.

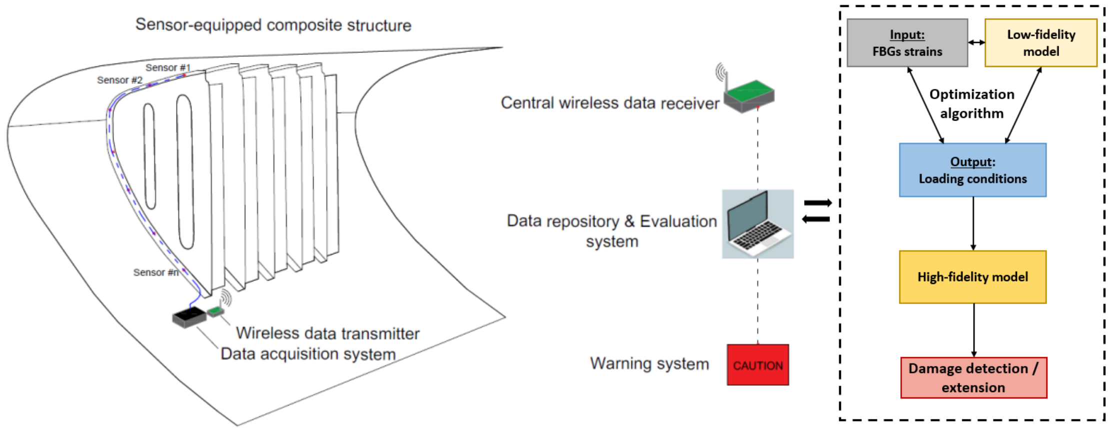


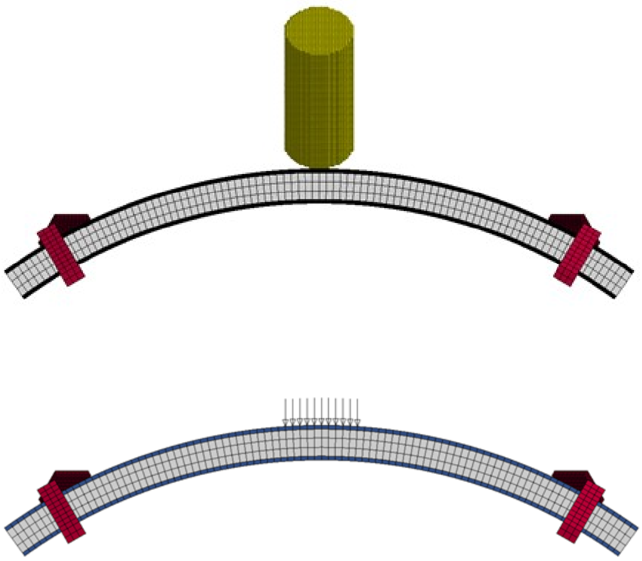
Figure 1. A schematic of digital-twin-assisted damage diagnosis concept

2. Modelling tools

This section briefly describes the physical-based FE models with different fidelity levels which were developed for a specific curved sandwich panel in a previous authors' investigation [3]. It should be mentioned that the creation and validation of these modeling tools constitute a preparatory and prerequisite step for the development of the DEA algorithm. In this study, the examined sandwich panel is 500 mm in length, 470 mm in width and about 26 mm in thickness. In essence, it is a slightly curved rectangular panel with a radius of 400 mm, whilst it is assumed that it consists of two symmetric quasi-isotropic lay-up ([(45/0/-45/90)2]s) CFRP faces with 2.88 mm thickness and a 20 mm thick polymer foam layer.

In the case of high-fidelity model, ply-based method (stacked-solid method) with 3D solid elements was adopted for the laminated skins. This technique can predict the separation of laminated plies on the grounds that each lamina is explicitly modelled. For delamination initiation and propagation modelling, a fracture-based contact algorithm is utilized at each lamina interface since it eliminates the drawbacks of cohesive elements. In the case of foam core modeling, the three one-integration point solid elements in through the thickness direction are considered adequate for capturing the bending and shear stiffness of panel. For the intralaminar damage, a modification of Hashin criterion is applied.

Regarding the LF model, it targets to reduce the high computational time of HF one keeping the modeling accuracy to an acceptable level. It is well known that the most representative the model is, the most time consuming is. Therefore the relegation of accuracy of damage modeling is applied using layered solid elements for skin modeling. The 8-node layered solid elements in LS-DYNA use one integration point per layer for computational efficiency capturing efficiently the bending stiffness and the through the thickness stresses like a 3D solid element. The second modification in relation to the HF model is that no cohesive elements are implemented into the CFRP faces for the capturing of interlaminar damage. Thus, the running time was significantly reduced (98%). In parallel, impulse-equivalent loading technique was implemented for the further mitigation of computational time. In essence, it is used a time-variable, distributed and impulse-equivalent load for the representation of bird impact force. The equivalent load is applied on a rectangular area whose the edge length is equal to the projectile's diameter (50mm). Regarding the loading shape, it is observed that it looks like a symmetrical bell for 45° oblique soft-body impact; therefore, it is simplified as a tri-linear loading curve. The figure 2 shows the model with the explicit SPH model of soft projectile and the model with the equivalent load. Detailed discussion about the modeling approach, the computational time and the validation process of modelling tools using experimental impact tests is given in [3].


(a)

(b)

Figure 2. Model including SPH soft projectile (a), and Impulse-equivalent model (b)

In previous authors' study [3], it has been concluded that the high-fidelity model can sufficiently approximate the experimental strain histories recorded by the FBG sensors, with the experimental delamination area accurately predicted. On the other hand, the LF model can rapidly predict the global vibrational response of sandwich panel, whereas the further transformation of the LF model based on applying an impulse-equivalent loading instead of SPH model of the soft projectile reduced the total computational time by 68%. In current research, all employed models were set using simplified equivalent loading due to a) the necessity for time efficiency and b) the parametrization of tri-linear loading curve in terms of loading rate, the magnitude, the unloading rate, and the impact duration.

3. Description of DEA algorithm

The MATLAB developed DEA algorithm consists of six (6) steps, which are in parallel the targets of current study, and they are executed in series. In the first step, the algorithm roughly estimates the position of the applied load by providing an initial arbitrary pair of values for load magnitude and impact duration. In essence, the LF model is running for different load positions and the algorithm evaluates the strain-time histories at the two measuring points. The target here is the minimization of root-mean-square (RMSE) error between the experimental values and the numerical ones, whereas the used searching algorithm of the 1st step is based on a user-defined logic scanning 35 points on the panel's surface. The output of 1st step is the rough estimation of load location and constitutes also the input of 2nd step. In the 2nd step, a fine searching procedure of load location follows and is based on the Pattern-search method [4]. The position of load is determined with an accuracy equal to the element size (i.e. 5mm in current research). When the location of loading has been defined, the 3rd step of algorithm is being activated for the calculation of loading rate changing the slope of loading curve at each running. The optimum value of loading rate is defined using the derivative-free Nelder-Mead Simplex optimization method [5] and the target experimental strain-time histories. Afterwards, the 4th step deals with the definition of loading magnitude, whereas the 5th step calculates the total impact duration using again the Nelder-Mead Simplex method. All the above steps are executed using only the LF modeling tool. Finally, the 6th step is a single running of HF model knowing the location and the time-variance of applied load. The necessary inputs for the running of algorithm are the FBG sensors data and an initial pair of values for the load magnitude and impact duration. The flow chart of DEA algorithm is illustrated in figure 3.

Regarding the assumptions of the proposed methodology, the current framework is formulated for high-velocity soft body impact and is restricted to the 45° oblique impact due to the available experimental tests; nevertheless, it can easily be modified for a normal impact scenario. The second assumption is that the area of applied pressure load is constant assuming that the projectile size is known, and the load is spatially static during the analysis. Therefore, the effect of projectile flattening cannot be captured due to the fact that it is an inherent limitation of modeling method.

As far as the execution time is concerned, both the numerical models and the DEA algorithm is highly improved for the minimization of running time. The execution time for a single run of LF model is 25 s, whereas for the HF model is 2hr and 19 min using an 12th Gen Intel i7-12700K 3.6 GHz processor and a 64 GB RAM. The total computational time of DEA algorithm is 3hr and 49min. Furthermore, it is necessary to be mentioned that the DEA algorithm is executed without any user intervention during the process.

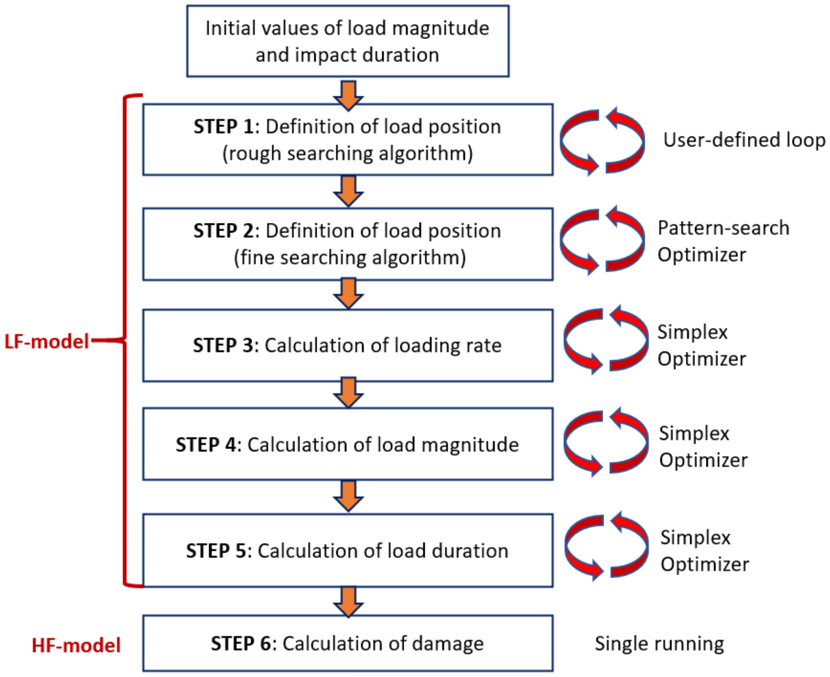


Figure 3. Flow chart of DEA algorithm

4. Results and Discussion

4.1 DEA algorithm's effectiveness

As described above, the execution of damage evaluation procedure is a stepwise process starting from the definition of load position. The distribution of RMSE error between numerical and target strain-time profiles on the panel surface for the 1st step is depicted in figure 4. The error minimizes at the point with coordinates X=260 mm and Y=-50mm which shows the location of the right-back corner of pressure load, whereas the fine searching routine finds the global minimum RMSE error at point with X=268 mm and Y=-50 mm which is extremely close to the experimental impact point.

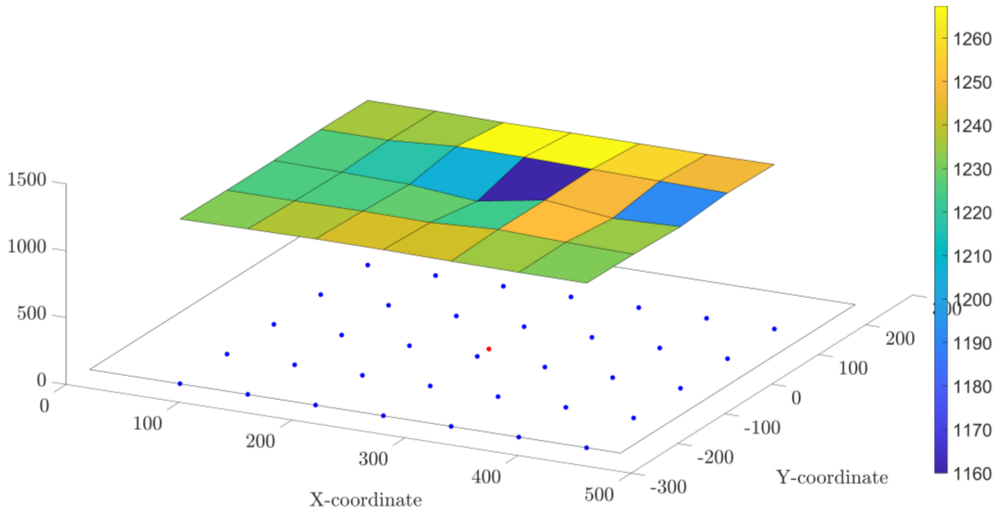


Figure 4. RMSE between numerical and target strain-time histories for 1st step of algorithm

The figure 5 compares the applied load versus time derived by HF/SPH model [3] with the time-varying load calculated from DEA algorithm. The HF/SPH model, showed in [3], is the high-fidelity numerical impact model created using SPH method for soft projectile representation.

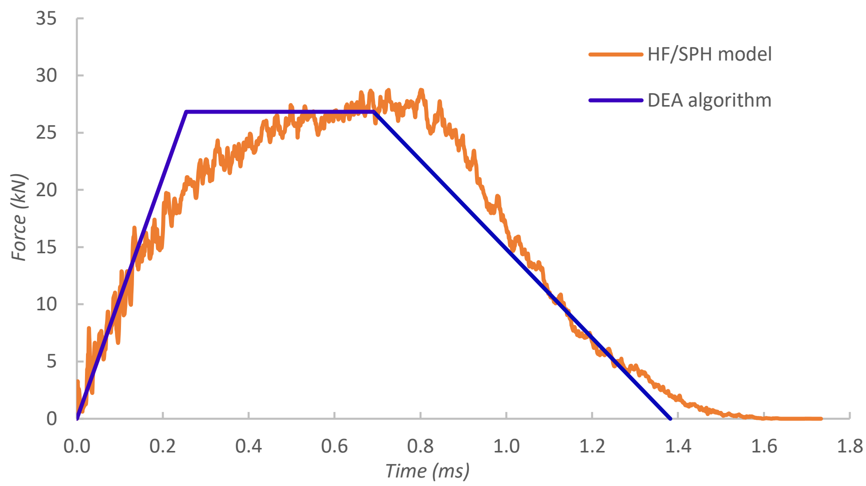


Figure 5. Comparison of the contact force-time response derived from LF/SPH model [3] and the calculated one from the DEA algorithm

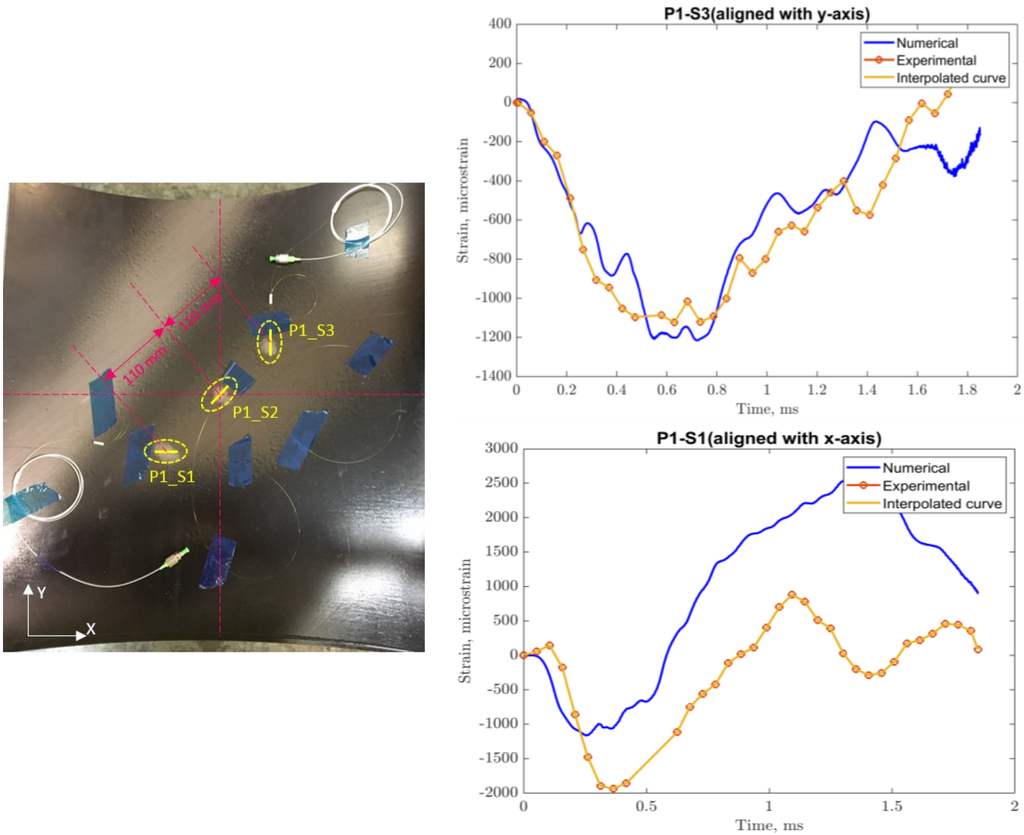


Figure 6. Comparison of experimental and numerical (DEA algorithm) strain-time profiles

In the case of HF/SPH model, the force-time curve of figure 5 is the applied force-time profile derived from the contact between composite panel and soft projectile. Comparing the responses, it is noted that the impulse difference is only 1.2 %. In particular, the impulse for

HF/SPH model is 24.6 Ns, whereas for DEA algorithm equal to 24.3 Ns.In parallel, the loading rate, the magnitude of load and the impact duration are on agreement with those of HF/SPH model of [3]. Consequently, it is infered that the DEA alogorithm has accurately calculated the impulse-equivalent load of impact event. The figure 6 shows the numerical strain-time profiles for the two measuring points P1_S1 and P1_S3 derived from DEA algorithm and the corresponding experimental ones [3]. From numerical point of view, each numerical strain-time profile was calculated from the output strain data of corresponding solid element located on the back side of target structure. In the case of P1_S3 point, the numerical profile is identical to the experimental one in terms of a) the initial slope of strain curve, b) the maximum strain during the impact event, c) the rise time at which the maximum strain occurs, d) the decay time and e) the trend of strain-time profile. Looking the result for P1_S1 point, it is infered that the numerical strain-time profile diverges from the experimental ones due to the load simplification according to the previous author's investigation [3]. However, it is in good agreement from the trend point of view. The conclusion here is that a pair of measuring points is necessary for better convergence of DEA algorithm and therefore more accurate results. Concerning the interlaminar damage, the total delaminated area by non-destructive evaluation is calculated equal to 16,875 mm^2, whereas the cumulative numerical damage is slightly larger and equal to 19,228 mm^2 (Figure 7). This discrepancy is due to the asymmetric delamination pattern observed in the experimental results. Acccording to [3], a heterogeneity of gelatine projectile and an imperfection in the target material might be possible reasons. However, the location and the extent of the actual damage in both directions have been precisely captured from the DEA algorithm, as shown in figure 7.

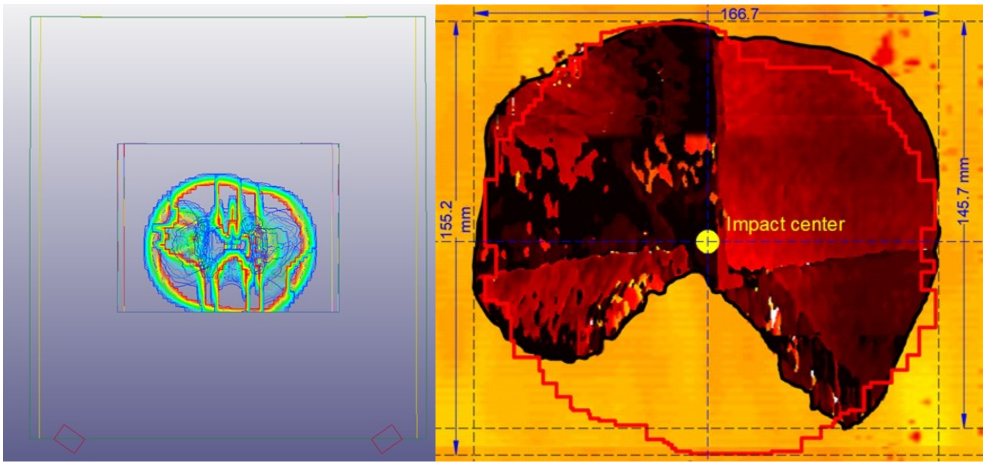


Figure 7. Comparison of total numerical delamination damage (red line) with the experimental one (black line) (right) and model with numerical delamination damage (left).

4.1 DEA algorithm's robustness

Apart from the algorithm's effectiveness, the robustness of methodology was assessed regarding the effect of the initial input values of load magnitude and impact duration. More specifically, 85 combinations of load magnitude-impact duration, which were derived from Latin-Hypercube Sampling (LHS) method, were studied. The influence of initial values on the load localization is presented in figure 8. 79 samples (viz. 92.9% of sampling) showed that the right-back corner of distributed load is placed at point with X=260mm and Y=-50mm; 4 samples (4.7%) locate the corner of load at X=440mm and Y=-50 mm; whereas, 2 samples (2.4%) provide the minimum error at X=260mm and Y=-150mm. Therefore, the DAE algorithm demonstrates high level of robustness.

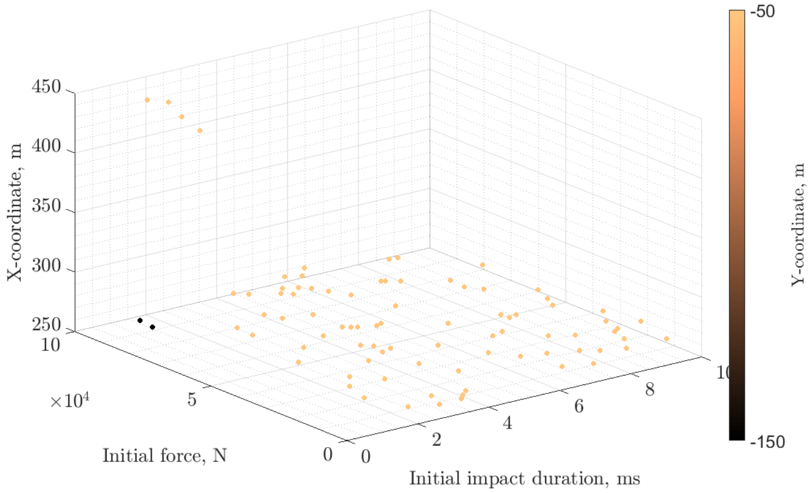


Figure 8. Inclueence of load magnitude-impact duration combination on the load localization

5. Conclusions

In the current study, an effective and highly robust digital-twin based algorithm for composite structure damage evaluation was developed. The damage localization and quantification with high precision is feasible using as input the FBG sensors strain-time profiles and without any user-intervention. The level of robustness of methodology can be maximized using multi-point strain data, whereas the time-efficiency can be increased implementing a surrogate model to the process.

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