

# Validation of an Abaqus impact wave propagation model

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**Abstract.** A finite element model for wave propagation due to an impact is very desirable, to enable the design of optimal sensor network configurations for Structural Health Monitoring (SHM) applications, to obtain a better understanding of wave propagation (especially in composite structures) and also to generate simulated (virtual) test data for SHM algorithm development. Therefore, an Abaqus explicit finite element (FE) model was developed for wave propagation from impacts. To validate such a model, a series of impact tests were performed with a drop tower on an aluminium clamped square panel, at different impact energy levels and different impact locations. On the panel, eight FBG and six PZT sensors were installed. These experimental results were used to validate the FE model, in which the impacts were simulated and the computed. PZT and FBG sensor responses were compared against the experimental results.

The paper will present the impact test setup, the finite element model and the validation results. The main focus of the paper will be the sensitivity analysis, identifying the model parameters that significantly affect the simulated impact sensor responses and their optimal settings. A good correlation between the numerical and experimental results was obtained.

**Keywords:** Impact wave propagation, Finite element simulation, FBG, Piezoelectric, Validation

## Introduction

An accurate finite element model for wave propagation due to an impact is very desirable, to enable the design of optimal sensor networks for Structural Health Monitoring (SHM) applications, to obtain a better understanding of wave propagation, especially in composite structures, and also to generate simulated (virtual) test data for SHM algorithm development. In order to validate such a model, a series of impact tests were performed with a drop tower on an aluminium square panel clamped in a support frame, see Fig. 1, at different impact

energy levels and different impact locations. On both panels, six piezoelectric (PZT) and eight optic fibre Bragg grating (FBG) sensors were installed. The experimental results were used to validate the FE model, in which the impacts were simulated. The computed PZT and FBG sensor responses were compared against the experimental sensor responses.

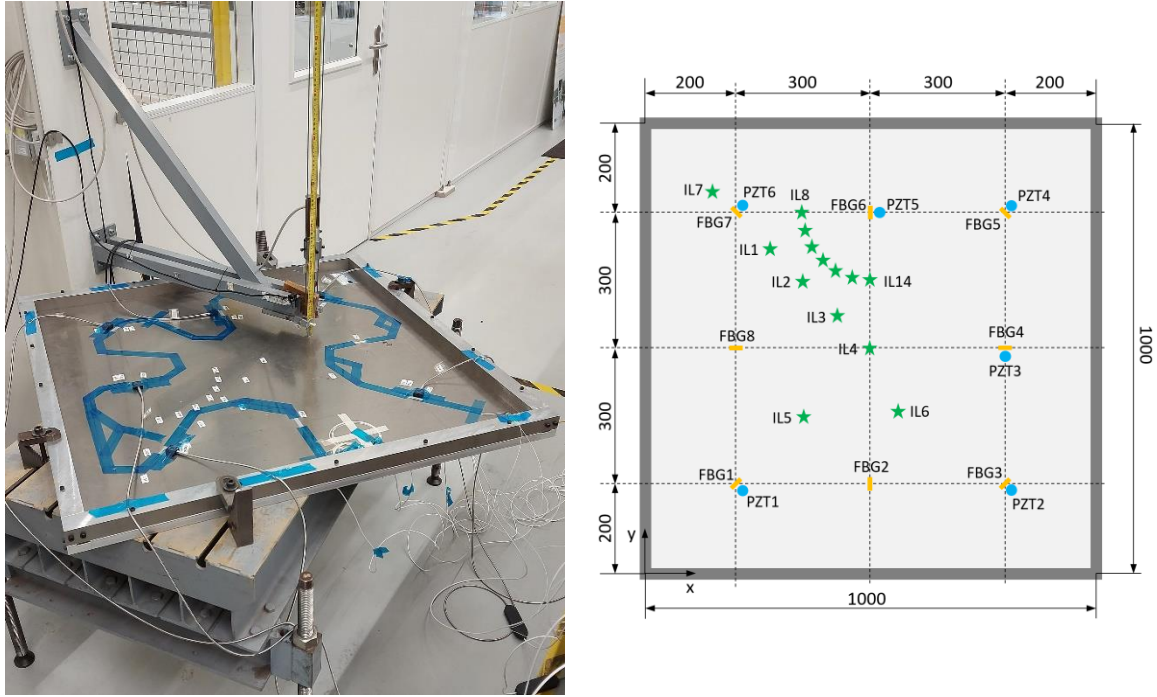
The objective was to develop an accurate (Abaqus) finite element model, while keeping computational costs as low as possible to allow simulations on realistic complex structures. The whole test setup, consisting of the plate, the support frame, the impact table and the impactor was modelled. With this (baseline) model, sensitivity analyses were performed for the various model parameters, in which the sensor strain time responses were computed at the PZT and FBG sensor locations for impacts on the plate. From these results the model parameters were determined that have no significant, a small and a large influence on the wave propagation in the plate. The computed PZT and FBG strain time responses were compared with the experimentally obtained sensor responses for different locations and energy levels.

Several authors [1-4] have looked at this problem before, but not provided a survey for all possible model parameters.

## 1. Experimental Set-up

The test setup consists of a flat Aluminium panel (1000×1000×3 mm) that was clamped at the edges by an aluminium support frame (40×30 mm) leaving an effective panel dimension of 960×960 mm. The support frame in turn was clamped to a very rigid metal impact table, see Fig. 1. A drop tower was applied by which a spherical impactor head of 16 mm diameter was dropped on the panel at various locations, also depicted in Fig. 1. At each location various impacts were performed with increasing impact energy, by adjusting the drop height of the impactor. Also, a number of impacts were performed with a few different impactor masses and impactor diameters. A force transducer, based on a strain gauge bridge, is integrated in the impactor measuring the impact force over time. The impactor speed at impact and rebound was measured by a light gate. Knowing the impactor weight, the impact and rebound energy could be determined.

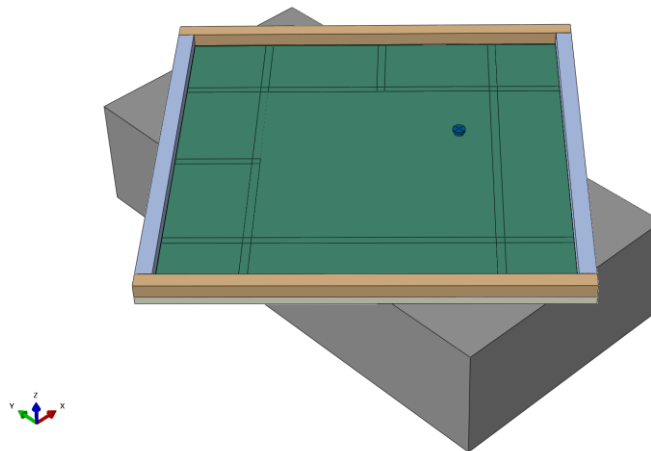
On the panel, eight FBG and six PZT sensors were installed, as depicted in Fig. 1. Different FBG orientations were applied to examine the sensitivity of the FBG with respect to the angle of incidence (not further discussed in here). A PhotonFirst Gator interrogation system [5] was applied to measure the FBG sensor responses at 19.23 kHz. A combined two and four channel TiePie USB Handyscope HS5/HS6DIFF data acquisition system [6] was applied to measure the PZT sensor responses at 1 MHz. Besides the FBG and PZT sensors, also acoustic emission sensors of Optics11 [7] are visible in the photo, but these do not measure the deformation of the panel but rather the acoustic vibrations and cannot yet be correlated to any simulation quantity and are therefore not be discussed in here.



**Fig. 1.** Experimental impact test setup (left) and sensor locations (right).

## 2. Finite element model

An Abaqus [8] explicit finite element model was built to simulate wave propagation due to impacts in the aluminium panel, see Fig. 2. The plate and aluminium support frame (both made of 2024-T3) were modelled separately using their measured dimensions. The measured panel weight was used to determine an accurate material density ( $2780 \text{ kg/m}^3$ ). A common value for the modulus of elasticity of 73.1 GPa and Poisson's ratio of 0.33, obtained from [9], were applied. Sensitivity analyses showed that both the modulus of elasticity (70-75GPa) and Poisson's ratio (0.3-0.35) didn't change the overall sensor responses and only caused some time dispersion in the order of one percent in the signal due to a change in stiffness. Hence, these model parameters only have a small effect on the simulation results.



**Fig. 2.** Finite element model of the impact test setup, with aluminium plate (green), support frame (blue and brown) and rigid impact table (grey).

Modelling the spherical hardened steel impactor head sufficed for the impactor model, adding a point mass to obtain the correct impactor mass. Both a rigid and elastic impactor were examined, as well as direct application of the (measured) force-time curves instead of the impactor.

The plate was modelled with linear quadrilateral shell elements S4R or 6 layers of C3D8R hexahedral volume elements. Volume elements resulted in similar sensor responses. Hence, shell elements, which are much more computationally efficient, were applied in all analyses. The C3D8R element type was also used for the support frame and the impactor. The impactor was located just above the plate, to reduce the computational effort, and an impact velocity was assigned to the impactor (using a Predefined Field) matching the measured impactor energy. The plate was subdivided into partitions around the sensor locations and the analysis results were only stored for the small sensor areas, to reduce the size of the ODB database.

Tie-constraints were applied to connect the plate to the support frame and the support frame to the table. The impact table was fully constraint using a rigid body constraint.

All simulations were performed with an Explicit Dynamic analysis for a 0.01 second time period with automatic time increments and a linear and quadratic bulk viscosity of 0.06 and 1.2, respectively. Sensitivity analysis showed that these values didn't significantly affect the computed sensor responses.

A sensitivity study of the mesh size revealed that an element size of 1×1 mm provided accurate impact responses at the sensor locations for the plate, and was therefore kept the same in all analyses.

Contact between the impactor and the plate was modelled by a General contact interaction between the impactor and the plate. It was verified that the sensor responses were not sensitive for the type of interaction, e.g. Surface-to-Surface with a Penalty contact or Kinematic contact method, using a Finite sliding or Small sliding formulation for the latter. A sensitivity analysis showed that the contact stiffness (up to a hard contact) had no significant effect, apart from very low values yielding incorrect responses. Hence, a contact stiffness of 1000 was applied throughout all analyses.

A python post-processing script was developed that computes from the simulated strain fields the strain response for an FBG sensor location in the orientation of the FBG. The script also computes the strain response for any PZT sensor from the average strain in both direction  $(\epsilon_{11}+\epsilon_{22})/2$ , see for instance [10].

### 3. Results and discussion

The sensitivity of the sensor responses for variations in all model parameters were examined. The model parameters that had no or only a slight influence on the sensor strain response, partly already mentioned above, were:

- Material properties of the stiff support frame: as long as it remains stiff compared to the aluminium plate
- Shell or volume elements for the aluminium plate
- Hourglass control parameter in element selection
- Modelling of the correct sensor size: if a sensor is located in a region with high strain gradients, the true gauge length should be considered otherwise the element in which the sensor is located suffices
- Sensor location or orientation: small deviations in sensor location or orientation (especially prone for FBGs) do not result in a significant difference in response
- Simpson or Gauss integration rule over thickness and number of integration points
- Small deviations in impact location

- Impactor contact friction coefficient
- Impactor plate contact interaction method (default General contact)
- Impactor rotational degrees of freedom: these were not important because the impacts were perpendicular to the plate surface

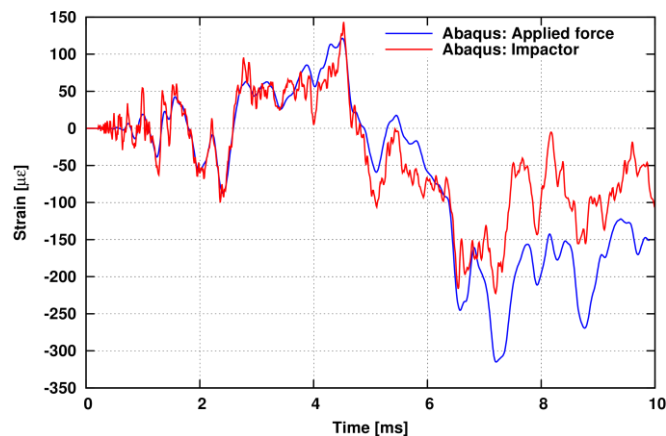
Model parameters that had a small influence on the strain response were:

- Poisson's ratio, Young's modulus, density and thickness of the aluminium plate, mainly influencing the speed at which the waves propagate in the plate, i.e. dispersion effect. A stiffer/lighter plate model also results in slightly lower strain responses.
- Small deviations, measurement inaccuracy, in impactor speed

The parameters that have larger influence on the simulated sensors responses are described in the following sections for impact location 8, see Fig. 1.

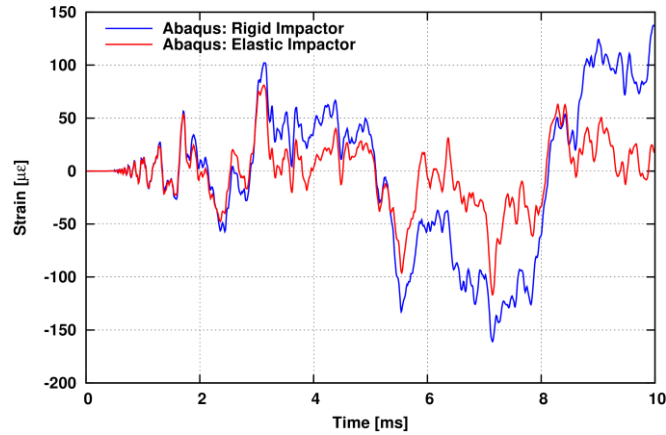
### *Impactor modelling*

One approach to model the impact, was to use the force data obtained by the force transducer from the drop tower. A second approach, was to model the impactor and give it the correct impact speed. The latter makes the model more realistic, somewhat more complex and more computational demanding, but enables the modelling of different impactor geometries. Application of the measured force response at the impact location resulted in too smooth sensor responses lacking higher frequency content, which are visible in the model with impactor, see Fig. 3. This also may be due to errors in the force measurements, although a sample frequency of 250 kHz was applied. Hence, in all analyses the impactor was modelled.



**Fig. 3.** Numerical strain response comparison without (left) and with (right) impactor model.

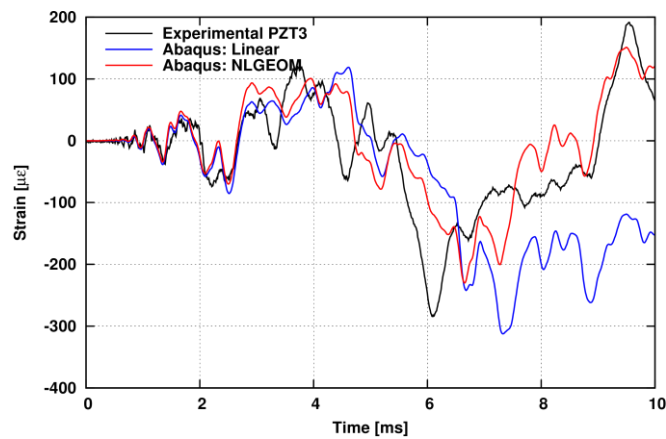
Modelling the impactor as rigid or elastic caused a significant change in sensor strain response, indicated in Fig. 4. The impactor stiffness has a significant change in contact area and subsequently on the generated wave field, see also [11].



**Fig. 4.** Strain response comparison for a rigid and non-rigid impactor.

### *Non-linearity modelling*

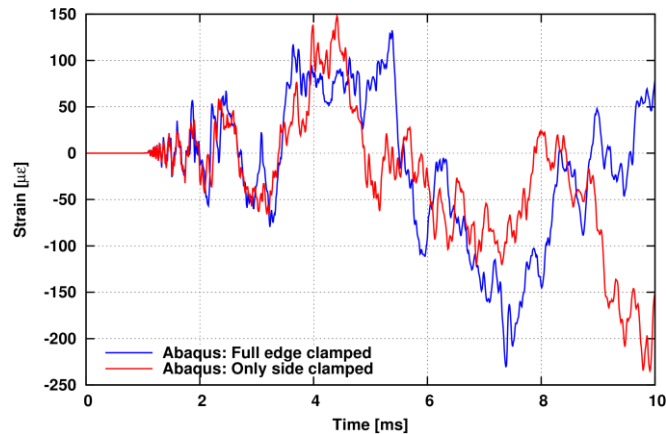
Enabling the non-linear geometry (NLGEOM) option in the step definition results in a better contact definition yielding a more accurate sensor response (Fig. 5) and was enabled in all analyses.



**Fig. 5.** Numerical and experimental strain response comparison for PZT3 without (grey-line) and with (blue-line) NLGEOM enabled.

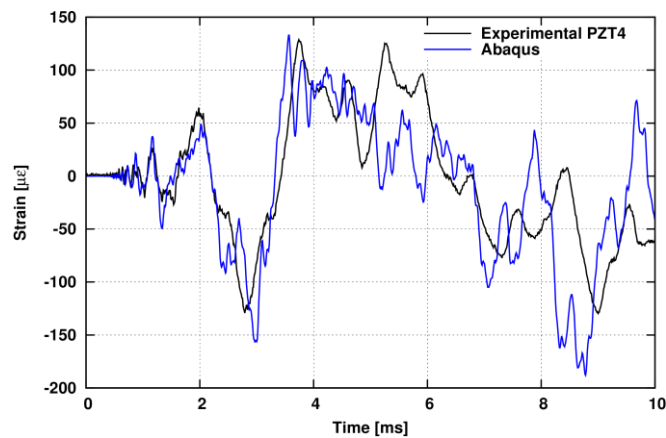
### *Plate boundary condition*

The computed sensor responses matched very well for the first 3 ms, but started deviating thereafter, see Fig. 7. This is caused by the added reflections from the boundaries arriving at the sensor location after about 3 ms. The boundary conditions are thus very important for this part of the response signal. The support frame yielded a less well-defined boundary conditions than anticipated. In Fig. 6, the sensor response is compared using a tie-constraints along the plate in contact with the support frame versus a tie-constraint only applied along the side of the plate. The two (most extreme) cases show a different strain response after about 3 ms when reflections arrive at the sensor locations. As indicated by [12], the sensor responses are strongly influenced by the impact duration, where long impacts cause a quasi-static response influenced by the plate size and boundary conditions. Short impacts have an interaction between impactor and plate unaffected by the plate size and boundary conditions, i.e. the plate-impactor contact stops before strain waves have travelled from impactor to the boundary and back.

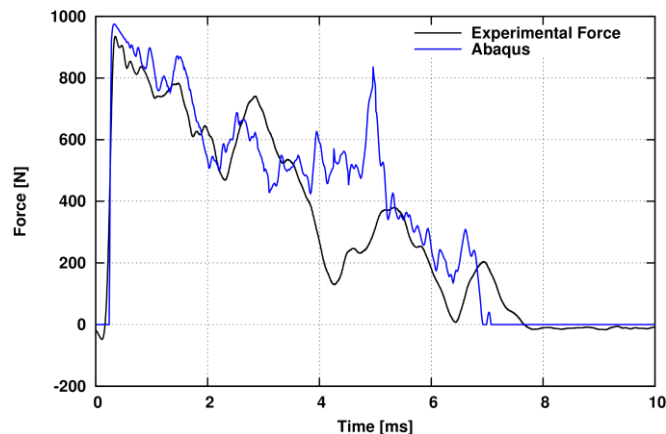


**Fig. 6.** Numerical strain response comparison for a fully clamped condition between plate and support structure (blue-line) and only tie-constraints applied to the side of the plate (red-line).

With the final model, the strain for first milliseconds matches the experimental data well, as can be seen in Fig. 7. The main difficulty was to correctly model the boundary conditions, even for the rigid support frame. This significantly affects the strain response after the first few milli seconds. After this, the boundary conditions play an important role and since they can't be modelled perfectly the strain start to differ from the experimental data. This can be observed in Fig. 7, where we can see that the sensor strain response extracted from Abaqus (in blue) matches with the experimental data (in red) for the first 3 ms after which it starts to deviate. Fig. 8 depicts the comparison of the numerical and experimental impact force over time, which also shows a good accuracy.



**Fig. 7.** Sensor strain response comparison between experimental (black-line) and numerical (blue-line) data.



**Fig. 8.** Impact force response comparison between experimental (black-line) and numerical (blue-line) data.

In the presented results the focus was mainly on the PZT responses because of the much higher sample rate (1 MHz) compared to the FBG data (19.23 kHz). Comparison between FBG and PZT response signals showed a strong correlation between both sensor types, demonstrating that both sensors measure similar responses.

#### 4. Conclusion

An explicit Abaqus finite element model to simulate wave propagation in a structure due to an impact was validated by comparing the computed sensor strain responses and impactor force responses with measured response signals for a flat aluminium plate. The sensitivity of the sensor responses was examined for each of the model parameters. A final model with the best values selected for each model parameters was used in the final comparison. The model was mainly validated using PZT sensor data due to the higher sampling rate. Model parameters that have a large influence on the strain response were:

- Enabling non-linear geometry (NLGEOM)
- Modelling the impactor as elastic instead or rigid
- Modelling the impactor instead of application of a measured force time signal
- Boundary conditions, these showed the highest influence after about 3 ms when reflections from the boundary conditions arrive at the sensor locations

The final model could predict the sensor strain and impactor force responses caused by an impact very well, up to the moment that waves, reflected from the boundaries, arrive at the sensors, which is mainly attributed to the imprecise modelling of the (not accurately known) interface between the plate and support frame.

A next step, is the validation of the model for a rectangular thermoplastic composite square plate and a 3-stiffener composite panel for which experimental impact measurement results [13] already have been collected.

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