An alternative to temporal down-sampling of DIC data in mechanical characterization

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Abstract. The ability to track and quantify displacements and strains using Digital Image Correlation (DIC) allows engineers to evaluate the mechanical behaviour of materials. DIC data is used in mechanical characterization to determine material model parameters using inverse identification methods. The accurate determination of the parameters affects the numerical simulations and their reliability in predicting mechanical behaviour. In inverse approaches, full-field strain measurements are often down-sampled to reduce the amount of data to be processed and to increase the computational efficiency of data processing. However, for nonlinear problems, such as plasticity, the loading path affects the response by default, so any temporal down-sampling of the strain field potentially leads to erroneous determination of the stress state and parameters. To address this problem, we propose an explicit stress integration algorithm whose computational cost is almost independent of the number of images (i.e., strain fields) considered in the stress reconstruction. The proposed method eliminates the need for temporal down-sampling of the experimental full-field data.

Introduction

Material testing is an important precursor to numerical simulations in predicting the mechanical behaviour of industrial parts and assemblies. The concept of Material Testing 2.0 (MT2.0) [1] strives to fully exploit the potential of DIC in material testing, as it abandons the paradigm of conventional (homogeneous) material testing and incorporates information-rich, image-based mechanical experiments for inverse characterization of mechanical material behaviour. The advancement of experimental techniques is accompanied by the development of identification strategies suitable for the MT2.0 concept, such as Finite Element Model Updating (FEMU) or Virtual Field Method (VFM) [2]. When the identification methods are applied to nonlinear problems, their most time-consuming ingredient is the stress reconstruction algorithm. They essentially solve an optimization problem that tunes the unknown model parameters to minimize the cost function. To this end, stress integration is performed at each DIC data point using the reconstructed strain increments. Consequently, the stress integration algorithm is required repeatedly depending on the unknown model parameters. The computational complexity of stress reconstruction using implicit stress integration algorithms has been repeatedly reported [3]. To reduce the computational effort, spatial and temporal down-sampling of the available full-field strain data is often used, which means that not all of the acquired data is used.

However, if the nonlinearity of the strain path strongly influences the stress reconstruction, the temporal down-sampling of the strain fields potentially leads to incorrect stress states that distort the output of the identification algorithm. Indeed, temporal down-sampling can lead to errors due to the linearization process in the integration of the stress path, especially for plasticity problems. If the deformation history is not properly taken into account, the reconstructed stresses are inaccurate and the sought model parameters are inaccurately identified. Although several studies have been conducted to quantify the influence of full-field strain measurement uncertainty on the identified parameters, their identifiability [4], the effects of DIC settings, noise level and smoothing, little attention has been paid to analysing the error resulting from temporal down-sampling.

To cope with the interrelated issues of strain path sampling, accuracy of the stress integration and computational efficiency, we are presenting an explicit stress integration algorithm that is independent on the number of images (and thus strain fields) taken into account in the stress reconstruction, as we had proposed in [5]. Theoretically, the proposed method eliminates the need for spatial and temporal down-sampling of the experimental full-field data used in the inverse identification algorithms like the nonlinear VFM.

Methodology

The problem of time sampling in elastic problems is irrelevant since the parameters can be inversely identified from any time frame acquired. Additional time frames can only serve to increase confidence in the experimental results. For nonlinear problems, on the other hand, the dependence on the strain path requires tracking along the load path. High accuracy can only be achieved with a relatively high sampling of the strain path. However, this means that all recorded time frames must be processed in an identification procedure, which is currently extremely computationally expensive. Identification algorithms also consist of stress reconstruction, which means that the stresses must be calculated for all captured points of the strain field in all time frames. Current stress reconstruction methods are based on the implicit radial return algorithm known from computational plasticity. A stress reconstruction converges iteratively to the solution for each time frame, so that the computational cost increases with the number of time frames.

In plasticity, explicit integration algorithms are not popular due to their conditional stability and permanent drift along the load path. However, in [6] we presented an explicit integration scheme that avoids the drift and is able to proceed with maximum possible stable sub-increments. Since there is no iteration, the calculation of the individual sub-increments is very fast. A time frame represents a single increment, but must be divided into sub-increments for stability reasons. If so, the size of a time frame – or the number of time frames along the entire load path – is irrelevant, as the algorithm always divides the load path into the stable sub-increments. This leads to a computationally efficient and stable explicit algorithm whose time consumption is almost independent of the number of time frames recorded.

Results

The characteristics of the algorithm were presented in the open-hole test [5]. The material is considered elastic-plastic and follows isotropic von Mises plasticity and linear hardening. Although general, a formulation has been adopted to the plane stress condition, which is most useful for DIC-accompanied experiments. It has been shown that even when using a synthetic strain field without noise, the error due to improper consideration of the strain path can lead to significant errors in the regions of considerable change, such as the elastic-plastic transition (Fig. 1a). The verification case also shows that the accuracy and robustness of the proposed explicit algorithm is comparable to the implicit one. However, a comparison of the computational cost shows a significant difference between the two algorithms and confirms the independence of the proposed explicit algorithm from the number of time frames (Fig. 1b).

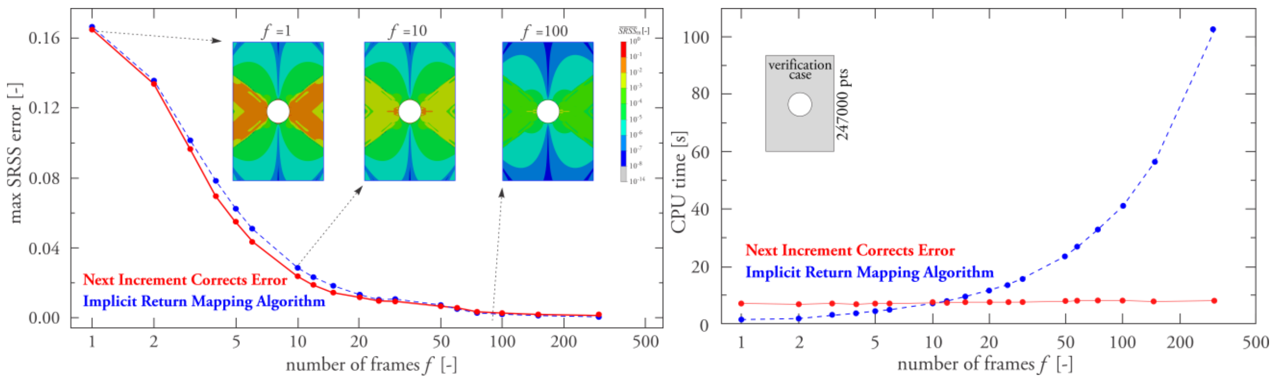

Figure 1. a) Error due to improper tracking of the strain path; b) Computational cost of the proposed explicit algorithm compared to the conventional implicit one [5]

Conclusion

In plasticity, a loading history must be adequately traced in order to correctly identify the model parameters. DIC data are available for different time frames, but for computational cost reason some of them are excluded from further processing. We have presented an explicit algorithm that is computationally almost independent of the number of recorded time frames, as it uses efficient sub-incrementation. Such an approach is an alternative to temporal down-sampling of DIC data, as the computational cost does not increase significantly when all time frames are included. The algorithm has been investigated using synthetic experiments and also validated by the real open-hole test.

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