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Simulation of delamination under impact using a global–local method in explicit dynamics

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ABSTRACT

Despite their interest, multi-scale methods based on domain decomposition are rarely used or even implemented within legacy codes. The reason is that their implementation is very demanding and that the robustness of their performance in industrial applications is questionable. In order to try to overcome these limitations, we recently adapted to the case of explicit dynamics a global–local multi-scale method [5]. So far, the method has been implemented in a Matlab code and validated on simple elastic cases. In this paper, we present the implementation of the method in Abaqus/Explicit using its co-simulation features to couple two separate Abaqus/Explicit analyses, running at different scales. The approach is illustrated in the case of the simulation of delamination under high velocity impact. A key aspect of the method, if compared to the one based on domain decomposition, is the fact that the global model covers the whole structure. This feature has been used to treat contact at the global level only, which greatly simplifies the implementation and enhances the computational performance of the method. The effectiveness of the method has been verified by comparing the results with other approaches already available in Abaqus/Explicit: the tie constraint between different regions of the model and the sub-modeling approach.

1. Introduction

The computationally effective simulation of large structures with complex non-linear local phenomena is still a scientific and industrial challenge. One of the main difficulties comes from the different length scales between the global response of the structure and the localized phenomena which can occur. To treat these questions in an effective manner, concurrent multi-scale methods have been developed first in statics. They are often based on domain decomposition techniques as the primal BDD method [26], the dual FETI method [14,13], or the mixed Latin scheme [23,24].

Due to the high cost of experiments, virtual testing is becoming essential for engineering workflows, as in the case of high velocity impact on composite structures, promoting the development of multi-scale methods also in dynamics. A number of studies have dealt with the extension of concurrent multi-scale methods to dynamics, leading to the design of multi-scale methods in space and time. Among them, some are based on non-uniform meshes and sub-cycling techniques, as in Belytschko et al. [3] and Daniel [11], others on the extension of the FETI decomposition method as in Gravouil and Combescure [18] and the following works. An extension of the mixed LATIN method in dynamics was also proposed in Boucard et al. [7,8]. These methods have proved all their potential in cases of local phenomena involving damage and failure, locally requiring short time increments and refined meshes, allowing to efficiently solve the induced vibration of the structure with much larger time increments and coarser meshes [10].

Despite these needs, concurrent multi-scale methods are not widely employed in standard versions of legacy codes, even though different attempts have been made to introduce them. This is due both to the high cost associated to their implementation and to their lack of robustness with respect to the variety of situations, such as complex meshes, model coupling of different dimensions, type of elements and so on, which legacy codes have to deal with.

A possibility to overcome some of these limitations is to make use of local–global approaches, where the global model extends over the whole structure and is never changed, while the local model concerns only the small parts of the structure where non-local phenomena or high gradients are expected to take place. An advantage of such approaches is that a large part of the tools needed for their implementation is available in legacy codes. Local–global approaches

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basically perform iterative sub-modeling computations to converge toward the exact solution of the full global–local coupled model. A drawback of these methods is that they could require relaxation in order to converge. So far, these methods have mainly been developed in statics, following the earlier work of Whitcomb [32]. Non-intrusive substitution global–local coupling has been introduced in Gendre et al. [15,16] for non-linear statics, in Guguin et al. [19] for shell-to-solid coupling, in Plews et al. [28] for thermo-mechanical coupling based on the Partition of Unity Method, or in Kerfriden et al. [22], Gupta et al. [20] and Passieux et al. [27] for the simulation of fracture based on XFEM.

For dynamic applications, sub-modeling techniques (see Abaqus [1]) are also available. They correspond to a sequentially run global-to-local approach: the global analysis is run at first with a coarse mesh and associated large time increments, then the local analysis of a small part of the global structure, discretized with a fine mesh with its associated small time increments, is analyzed, driven by boundary conditions extracted and interpolated from the global solution. Such coupling can be defined “completely non-intrusive” because the implementation is simply based on an output–input data process between two analyses and “one-way coupling” because the data exchange is from global to local and the global solution is not corrected after the local one. Another available method in Abaqus is based on co-simulation. Co-simulation is generally employed for coupling two ore more software, for multi-scale and multi-physics problems.

A general co-simulation scheme is presented in Sicklinger et al. [29] for coupling analyses with the same time increment. The domain decomposition method for implicit–explicit couplings through co-simulation is described in Chantrait et al. [9], coupling Zebulon and Europlexus, or in Gigliotti and Pinho [17], coupling Abaqus/Standard with Abaqus/Explicit. Also, an acoustic–dynamic coupling for automotive brake systems is described in Esgandari and Olatunbosun [12], with Abaqus/Standard (i.e. the implicit version of the code) used for the complex eigenvalue analysis and Abaqus/Explicit for the finite elements dynamic analysis. A possible limitation of domain decomposition based multi-scale methods in dynamics is the requirement of a pre-subdivision and calibration of the model topology. In case of an evolutionary process, as in the case of delamination under impact, this would require the re-definition of the whole model, one of the most demanding tasks in engineering analysis of complex problems.

In order to try to circumvent this limitation, a concurrently run, global–local approach for explicit dynamics, which will be referred to in what follows as the “substitution method”, has been introduced in Bettinotti et al. [4] as a weakly intrusive method. In contrast to the sub-modeling technique, it is based on a two-way coupling exchange between the global coarse mesh, extending over the whole structure, and the fine mesh of a local small region, where a more detailed solution is required. Separate explicit dynamics analyses of the two meshes are concurrently run. The method allows each explicit analysis to march with its own time increment, dictated by the mesh size for stability requirements. As in sub-cycling techniques, the two analyses are synchronized at the end of the largest time increment ensuring that both interface velocities and accelerations are equal for each global time increment between the global and local scales (see Section 3.3.2). The equilibrium at the interface of the local domain is then achieved iteratively at each global time increment as explained in the paper. One appealing feature of explicit dynamics is that iterations concern the local domain only, the associated global modifications taking place at the next global time increment limiting therefore the cost of iterations, which, thanks to a reformulation in a more efficient iterative scheme in Bettinotti et al. [5], are limited between one and three.

So far, the substitution method proposed in Bettinotti et al. [4] has been tested on simple examples using a Matlab prototype. In the case of linear elasticity, the comparison with the domain decomposition method, proposed in Gravouil and Combescure [18] allowed to verify the method. In order to deal with problems of industrial interest, as the one of delamination under impact taken as reference example in this paper, the method has to be used within a legacy code, here the finite element code Abaqus/Explicit.

In statics, the Abaqus global and local models used in the proposed non-intrusive method can be coupled by making use of a Python script. This procedure would be much too costly in explicit dynamics where hundreds of thousands of time increments are often required even at the global level. The first problem to be considered is therefore the implementation of the method within the legacy code. The following questions need then be answered. What type of development does this require? How much of the standard capabilities available in Abaqus co-simulation engine can be taken advantage of? Does the proposed scheme offer a weakly intrusive way to be introduced in the core of a legacy code as it is expected?

The second problem that we consider here concerns the difficulty exhibited by multi-scale methods in space and time based on domain decomposition in the case of constraints extending over different domains and integrated with different time increments. In that case, the finest time increment has to be used for every domain subject to the constraint, which limits the interest of those methods in quite a number of applications. For this reason, we investigate here the possibility to take a given constraint (here the contact condition) only at the global level. To examine these two issues, an example of interest for our partner Airbus has been chosen, the one of an impact of an object on a composite panel.

Besides the present introduction, the paper is organized according to the following scheme: Section 2 will introduce the structural problem taken into exam and the model currently used by engineers, Section 3 will present the multi-scale strategy with the introduction of the coupling to a coarser model to reduce computational cost and with the recall of the substitution method formulation, Section 4 will show the results and validate the proposed approach with respect to other approaches already available in Abaqus/Explicit, like tie constraint and sub-modeling. Conclusions and prospects (Section 5) close the paper.

2. Structural test case

2.1. Modeling considerations for composite structures

Let us consider a calibration test on a composite panel as the one described in Fig. 1. If one wishes to predict directly the results of such an impact, we should ideally introduce in the modeling the different types of damage that happen at the so-called “meso-scale” of the ply (fiber failure, matrix cracking, fiber–matrix debonding) and at the interface between plies (see Allix [2]).

What would the consequences of the use of such meso-scale model be? Let us consider a typical panel of 1 m^2 with forty plies for a typical impact duration of three milliseconds. Each ply should be discretized separately, the typical scale being here a tenth of a millimeter, the interfaces between each plies should be discretized at least accordingly (and possibly with a finer mesh if one wish to properly describe the process zone at the delamination front). The associated finite element problem size corresponds to about three billion d.o.f.s, with some hundreds of thousands of time increments in explicit dynamics. This is not the type of computation that can be performed today in engineering, that due to the lack of resources and time.

The procedure that is usually followed is based on the knowledge coming from previous tests on the same type of structures. The delaminated interfaces, usually one or two, are explicitly introduced in the model, while the other plies are stacked in multi-layered shell elements. We refer to this type of model as “pseudo-meso-scale” model. In this type of model for each stack, the plies stiffness is averaged through the thickness and governed by damage laws. Moreover, the interface parameters are calibrated in order to be able to use large elements depending on the number of plies. Such kind of ad hoc model is capable to reduce by orders of magnitude the number of degrees of