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Preparation of Finite Element Models: The Use of an a Posteriori Mechanical Criterion

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Abstract

A geometrical model needs to be simplified to perform a FE (Finite Element) analysis. Several tasks of shape processing are required during the FE model preparation phase. An appropriate geometric model and a suitable set of geometric and mechanical operators may significantly improve the efficiency of the whole process. Our approach is based on the use of a reference geometric model that is the polyhedral representation of a component. To simplify the component shape, we utilize some geometric operators associated to mechanical hypotheses, so that all the component shape changes take into account the mechanical hypotheses related to the FE model. Since a priori criteria acting before the FEM solving process cannot efficiently quantify the influence of a shape simplification on the accuracy of FE simulation results, a mechanical a posteriori criterion has been implemented, which analyses the impact of shape changes on the simulation to tune the simplification process. Therefore, we perform a first FE computation on the simplified model and use the results to assess the mechanical influence of shape simplifications that have acted on the model. If some details prove to have influence on the mechanical behaviour, the model on which the FE analysis is performed needs to be redefined. Therefore, we are able to adapt the model according to a desired accuracy of the analysis results. In this article, we describe all the process that has to beset up to perform this adaptive modelling of components.

Categories and Subject Descriptors (according to ACM CCS): J.6 [Computer Applications]: Computer Aided Engineering

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1. Introduction

To be tractable, the mechanical simulation of a product requires a simplified representation of the component. The current simulation tools and particularly the Finite Element Method (FEM) unlikely take into account all the shape details, since it could be very tedious or even harmful with regard to the simulation process. So, models generated during the design process need to be prepared before performing a mechanical simulation. The generation of models for structural behaviour simulation purposes needs several steps of adaptation, idealization and detail simplification [MCC98], [DPS94], [FC00]. The quality of FE computations can be highly affected by these simplifications, because there is a complex relationship between the shape of the object, its boundary conditions and the stresses and strains characterizing its mechanical behaviour. Therefore, the choice of details and the evaluation of their mechanical influence are of primary importance [LCP03]. In an a priori approach, based on the user's expertise, geometrical criteria linked to the mechanical properties of the problem could be considered [FL05], [FML04], [CMVT95]. Anyhow, a priori criteria are not enough to quantify the influence of a shape simplification on the results of a FE simulation, because they can hardly predict strictly mechanical parameters like strain energy or stresses. A priori criteria are better suited for criteria that incorporate geometric quantities having a mechanical meaning like inertia, mass, etc [FML04]. For instance, errors generated by a hole removal will depend on the dimension of the hole but also of its location with respect to the boundary conditions applied on the component. Therefore, the area containing this form feature could have either low or high stresses. To evaluate the influence of its position, a mechanical criterion needs an information about the location of highly stressed areas and hence an estimation of the analysis results.

Therefore, a good mechanical criterion needs an a posteriori process, where the influence of the simplifications is assessed from the results obtained from a first FE computation, performed on the simplified model. Thus, the user obtains information in order to validate the quality of his/her FE results in relation to the simplifications performed and the desired accuracy of the FE solution.

The use of an a posteriori FE error estimator can be incorporated in an adaptive process of geometric simplification [MF05]. The shape of the simplified part can be refined after a first simulation, depending on the mechanical influence of its removed details. This adaptive simplification process is described hereafter and the paper is structured as follows. Section 2 describes the overall scheme of the adaptive simplification process; section 3 introduces the shape simplification concepts and some of the corresponding operators. Section 4 highlights how the a posteriori error estimator can be incorporated into the simulation process to assess the influence of details and gives illustration of its results.

2. The overall adaptive simplification process

The Figure 1 summarizes the complete adaptive modelling process. In order to make easy its integration into a product development process, input models considered can be either CAD models, i.e. B-Rep NURBS models, or digitized models or pre-existing FE meshes. Coping with this variety of models speeds up the product development process, because simulations can be initiated from a much larger range of configurations.

Acting as common denominator among all the input models, polyhedral models form an intermediate model software environment where the simplification process takes place. At this stage, the simplification criteria are a priori ones, such as mass and inertia variations.

The details suppressed are stored before evaluating their influence according to the a posteriori mechanical criterion.

Then, starting from the simplified model, a FE mesh is generated and boundary conditions are added to form the input of the FE computations.

In order to evaluate the influence of details removed from a mechanical point of view, a FE mesh is generated for each of them and a sub-domain is built for performing a local FE analysis.

The influence indicator is based on the results of FE computation for the simplified model and of FE computations over each detail. It gives a feedback about the contribution of each detail compared to the FE solution for the simplified model. Here, the comparison is based on the strain energy ratio between each detail and the simplified model. Therefore, very low values of the indicator validate to the user the removal of the corresponding details.

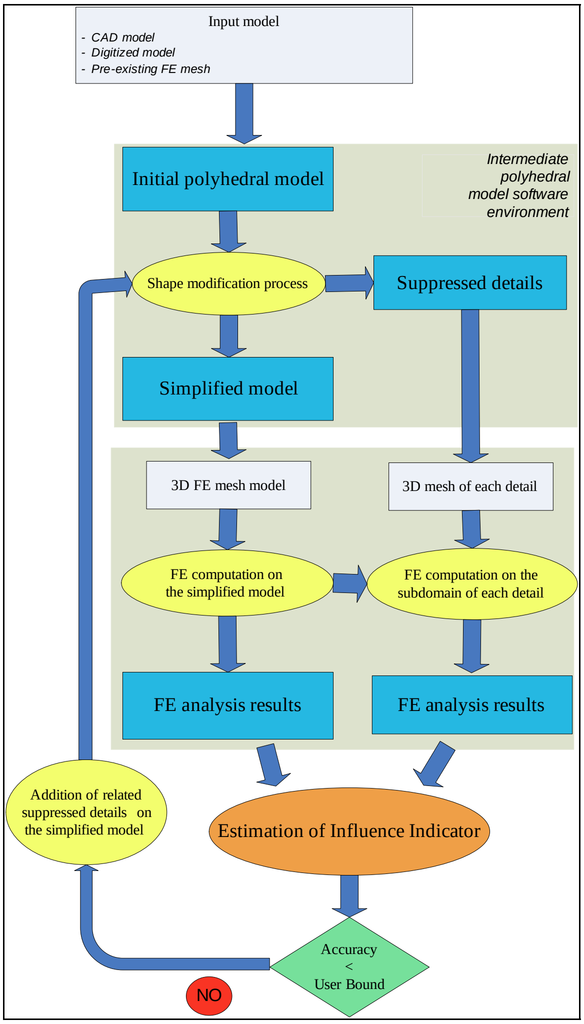

Figure 1: *Adaptive modelling process*

3. Shape simplification process

For the reasons stated at the previous section, an intermediate polyhedral model is used as reference model for the structural analysis preparation. Therefore, all the shape modifications operate on this geometric model.

Several reasons can be put forward to motivate the use of a polyhedral model as intermediate model between a CAD and a FEA environment [FL05]. CAD models suffer from limitations of the file transfer process generally occurring during the link with a CAE environment and restricting the type of shape changes that can be operated on the object. Indeed, the NURBS model used for describing a CAD model leads to tedious geometric modifications to get details removed. Moreover, polyhedral models, very close to FE meshes manipulated during the simulation process, are quite familiar to simulation experts. Therefore, generating a polyhedral model from a B-Rep NURBS one with a deviation not larger than that one produced by the FE mesh generation process is acceptable, and allows obtaining a common software environment. A polyhedral representation also allows accepting a larger variety of data as input, so widening the circumstances where performing a FE analysis during the product development process [HLGF05]. In addition to tessellated models coming from CAD systems, digitised models can be used without constructing their CAD representation. Similarly, pre-existing FE models used for previous FE analyses can be re-used as basis for further shape transformations, meeting the objectives of new FE analyses.

3.1. Operators for FE model preparation

The initial model needs to be simplified in order to perform the FE analysis. Two categories of operators, aiming at transforming the component shape, are used [FL05]:

- Skin detail removal operators. They change the component shape without modifying its topology. The simplification operator is based on an iterative vertex removal and local remeshing process;
- Topological detail removal operators. They change the component topology while preserving the dimension of its geometric manifold. Some geometrical criteria are used, detecting edges which delimitate the hole faces. When each hole has been identified and characterised as a connected subset of faces, the topological operator removes nodes, edges and faces defining this subset and remeshes the gaps formed by each edge loop corresponding to a hole boundary.

In Figure 2, the simplifications that we can perform with these operators are showed.

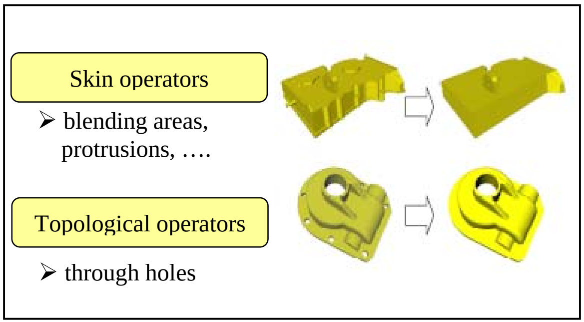

Figure 2: *Examples of simplifications performed with the used operators.*

Although we focus on the application of an a posteriori criterion to estimate the influence of each simplification, even the first stage of simplification needs to be conducted according to some criteria.

Firstly, the simplification operators need to be consistent with the boundary conditions applied to the component. To identify the geometric details that could be removed, it is essential to estimate the physical behaviour of the component in the context of a given problem of structural analysis. This estimation is based on the user's know-how and on the objectives of the simulation process. Therefore, in first stage of simplification, the shape modifications on the polyhedral model are performed in accordance with a priori mechanical criteria that control all the shape modifications. To this end, we enrich the polyhedron with the map of FE sizes used to generate a FE mesh. This map reflects, for each area over the model, the desired size of elements modelling some mechanical parameters as for example the stress or the strain fields for a given FEA. It could also be interpreted as the minimum discretisation level of the object geometry required for a FE analysis. Therefore, the comparison between the target FE sizes and the size of the edges defining the input polyhedral model allows the geometrical operators to remove more vertices in areas where a shape change is considered as not affecting analysis results. The FE map of sizes acts as a geometric representation of the mechanical behaviour of the component and can be easily generated by the user since it expresses the gradients of mechanical parameters, i.e. small FE are located where stress concentrations take place, large FE are located in areas where the stress values stay constant.

We use the concept of map of FE sizes to generate a geometric envelope around the component. Figure 3 illustrates en example of discrete envelope (Figure 3a) around a component to characterize the map of FE sizes attached to an analysis (Figure 3b). The size of the spheres reflects the FE sizes; indicates the location of the details; and bounds the shape variation of the component during the adaptation process.

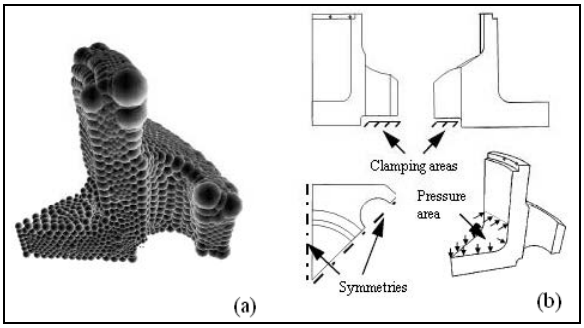

Figure 3: *An example of FE map of sizes (a) attached to a polyhedron to drive the a priori simplifications with regard to the target analysis (b). Each FE size is represented by a sphere.*

The simplification process, based on a vertex removal algorithm, is combined with an inheritance mechanism, so that the values of sphere radius attached to the removed vertices are kept active entities of the discrete envelope all along the decimation process. At each step of the simplification process, the inheritance mechanism is achieved with a redistribution process of the map of FE sizes over the faces forming the remeshed area. The combination of vertex removal operator and the inheritance process helps to formulate the shape restoration criterion, imposing that the decimated polyhedron respects the geometry of the model and stays within the discrete envelope.

3.2. Identification and storage of “simplification details”

The described operators help to generate a simplified model for the FE analysis, taking into account some a priori mechanical criteria, such as the map of sizes, which can drive the simplification process.

Our aim is to make use of an a posteriori criterion, which acts after the FE computation to estimate the accuracy of the FE analysis results on the simplified problem. The proposed a posteriori criterion evaluates the influence of all the removed details on analysis results. In order to reach this objective, a local FE computation over the neighbourhood of the removed detail is needed.

We will consider as a single detail, that we name “simplification detail”, each adjacent set of faces whose removal is considered by some a priori evaluations not affecting simulation results. Apart from the way of identifying a “simplification detail”, we need to store the related information in order to use it for the subsequent estimation performed by the a posteriori criterion.

The concept of “simplification detail” can be applied to any kind of detail removed during the simplification phase. If we deal with models having also a CAD representation, information about faces belonging to a form feature can be added to the geometry of the polyhedral model. This is possible when the software environment generating the polyhedral representation of the CAD model is part of the intermediate polyhedral model software environment (See Figure 1) [HLGF05-1]. In fact, we are able to attach different kinds of data to the polyhedral model, thus knowing when the whole set of polyhedron faces, which corresponds to the form feature, is removed. In this case, the form feature is considered as “simplification detail”.

Even if no CAD data are available, the proposed topological operator allows to recognize and to remove topological details, like through holes. If a priori evaluation considers that an existing through hole has no influence on the FE analysis results, the whole set of facets forming the topological detail is identified and removed. In this case as well, the suppressed detail is stored, in order to compute its real influence on simulation results during the a posteriori evaluation.

In a more general situation, where the simplification was corresponding to shape adjustment and not to a whole form feature removal, after an a priori simplification on the model, we can recover all the faces no longer existing in the simplified model. In a more general situation, where the simplification details correspond to shape adjustments rather than a whole form feature removal, it is again possible to locate areas corresponding to the details removed. After an a priori simplification on the model, we can recover all the faces no longer existing in the simplified model that define these sub domains. Sometimes, shape changes are so small that it is not necessary to evaluate their influence over FE analysis results, so we do not consider as details slight shape refinements. We keep memory and consider as part of actual details only faces belonging to areas where important shape changes have occurred. The adjacency of these faces is then analyzed, and each set of adjacent faces is considered and stored as a single detail.

Figure 4 shows an example of a model before and after having applied the simplification operators. All the changes are in accordance with an a priori estimation performed by the user, who uses a FE map of sizes reflecting the size of FE elements desired for the mechanical analysis.

Figure 4: *Initial and simplified models*

All the obtained “simplification details”, which have been identified and stored for the a posteriori analysis, are showed in the Figure 5.

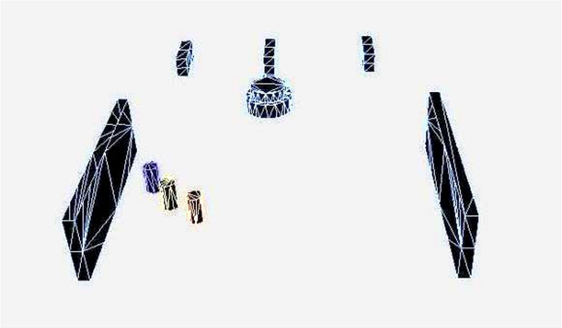

Figure 5: *Simplification details identified as subset of the initial model.*

4. A posteriori process

After creating a volumetric mesh of the simplified model and applying the desired boundary conditions (see Figure 6), we are able to perform a linear static FE computation with it. Once the solution of the FE problem is obtained, the a posteriori mechanical criterion can operate. The proposed estimator uses results of the FE computation on the simplified model about mechanical quantities, like the strain energy inside the structure. Some results of the FE computation become the boundary conditions of a sub-domain built in the neighbourhood of each detail removed, so that an approximated local computation can be performed on this sub-domain. The influence of each detail is then evaluated using the energy norm of the difference between this approximated solution involving each detail and the solution on the simplified problem.

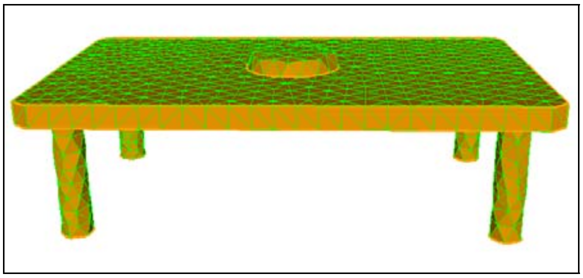

Figure 6: *Volumetric mesh of the simplified model.*

4.1. Generation of the domain for the local computation associated to each detail

In order to build a sub-domain around each removed detail, we need first to create the volumetric FE mesh for each of the stored details. To build the 3D FE mesh of the detail, we need to have a closed domain. Therefore, if the detail is made up by an open set of adjacent faces, we have to identify its boundaries. Then, a remeshing scheme is applied to obtain a closed polyhedron that can be used to generate the 3D FE mesh.

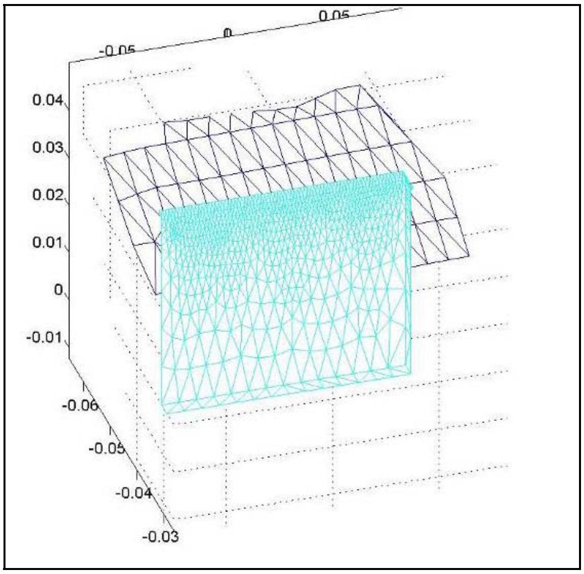

Figure 7: *Example of a FE mesh around a simplified detail for the local FE computation.*

The FE sub-domain around the 3D FE mesh of the detail is constructed using the volumetric FE mesh of the simplified model. The resulting mesh proves to be non-conform, i.e. a mesh is considered conform if the intersection result of two distinct elements is either empty or a vertex or an edge or a face (if the elements are volumes) common to the considered elements [FG99]. Since the detail and its neighbouring sub-domain are nearly two independent domains, we face a situation where some elements have in common only a portion of one of their faces.

We define a linear relation for linking the two 3D FE meshes and we perform a FE analysis on the resulting domain. Since some tests showed that the accuracy of the indicator proved to be not significantly influenced by the non-conformity of the FE mesh, we do not care about it.

We perform a local FE computation on the domain thus identified. The boundary conditions for the local computation are the node displacements of the domain boundary resulting from the FE computation on the simplified model.

4.2. Results of the a posteriori indicator

After the approximated local computation, we can apply our indicator for estimating the influence of the error generated by the suppression of the considered detail.

According to a threshold value of the FE results accuracy prescribed by the user, the indicator evaluates whether the detail suppression has some influence on simulation results or not [MF05]. If a detail proves to have a significant influence over the mechanical behaviour, it can be re-incorporated in the simplified model, which is so redefined. A well-tuned FE simulation can be then performed on the newly adapted model.

Hereafter, an example of adaptive modelling is presented. Figure 8 illustrates the initial problem. The boundary conditions are the following: the four table's feet are clamped and a force is applied on the cylinder 1. Figure 9 shows the first simplified model, where twenty-six details have been initially suppressed.

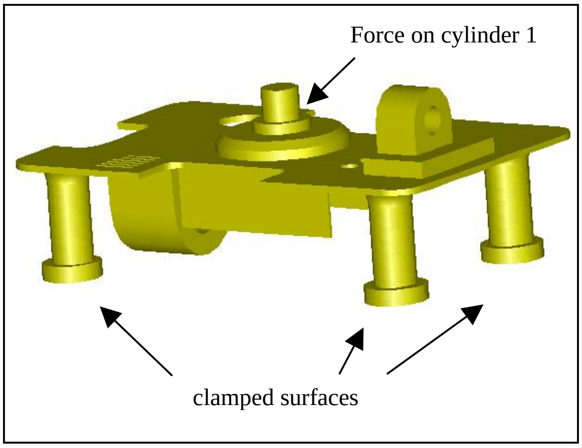

Figure 8: *Initial model with related boundary conditions*

After performing a simulation on the simplified domain, we compute the influence of each detail suppressed. For any accuracy less than 30%, we realize that the simplified domain needs to be refined. Figure 10 shows two refined models, depending on the desired accuracy. The simplified domain of Figure 10a enables a FE results accuracy of 1%, while that one of Figure 10b enables an accuracy of 10%.

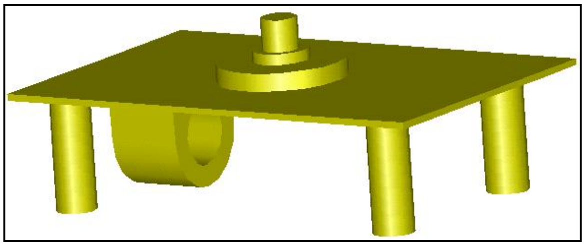

Figure 9: *First simplified model*

(a) (b)

Figure 10 *Adaptive simplified domain depending on the threshold value of accuracy: 10% for case (a) and 1% for case (b)*

5. Conclusions

The quality of a FE computation can greatly depend on the shape simplifications occurring on a geometric model during its preparation for the structural analysis. The user's expertise is often not enough to choose what simplifications performing on the model. Although geometrical criteria linked to the mechanical properties of the problem can be used in an a priori approach, they are not able to quantify the real influence of a shape simplification on the results of a FE simulation.

Therefore, we have chosen to implement an a posteriori approach, so that the user gets information about the quality of his FE results. We have developed an a posteriori mechanical criterion. It uses results of a first finite element computation on a model simplified a priori to quantify the influence of all the shape simplifications occurred on the model. For each detail simplified, an error indicator is assessed.

This a posteriori approach could be utilized in an adaptive process of geometric simplification. Depending of a value of accuracy established by the user, we estimate the mechanical influence of each removed detail after performing a first simulation. In this way, we are able to redefine the domain of the simplified geometric model.

At present, we have automated the first part of the process, concerning the operators that identify and store the simplified details. The future work will deal with the automation of the complete adaptive modelling process. We will so able to reinsert automatically into the model details that, according to the a posteriori analysis, have proved to have influence on simulation results.

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