Structural Analysis based on the Product Model Standard IFC

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Summary

In this paper we present a computer aided method supporting co-operation between different project partners, such as architects and engineers, on the basis of strictly three-dimensional models. The center of our software architecture is a product model, described by the Industry Foundation Classes (IFC) of the International Alliance for Interoperability (IAI). From this a geometrical model is extracted and automatically transferred to a computational model serving as a basis for various simulation tasks. In this paper the focus is set on the advantage of the fully three-dimensional structural analysis performed by *p*-version of the finite element analysis. Other simulation methods are discussed in a separate contribution of this Volume (Treeck 2004). The validity of this approach will be shown in a complex example.

1 Introduction

A strictly three-dimensional modelling technique is considered as a basis for a structural simulation using high order solid finite element analysis. This approach is part of an advanced framework which serves as a preprocessor based on three-dimensional models for general numerical simulations. Besides the structural analysis, the framework currently supports indoor air flow modelling, combined with a multi-zone network model for the building energy simulation. Using the Eurostep IFC Toolbox (Eurostep 2000), being an object oriented C++ implementation of IFC scheme representations and providing interface functionalities to access and manage instances of a product model, we derive an intermediate geometric model from the various geometric representations contained within the IFC building product model data. Since, among others, each IFC object contains its individual BRep representation, we create a 'consistent' (e.g. free from gaps) and 'corrected' (e.g. due to intersections) geometric model based on the ACIS geometric kernel (ACIS 2004). In a next step, this geometric model is decomposed into a so-called connection model, which consists of ACIS bodies and faces. Having this specific set of geometric objects, the numerical discretization of the geometry is initiated. For the structural analysis with the *p*-version of the finite element method, we present the automatic generation of a mesh with hexahedral elements based on the original IFC data set. Thereby the hexahedral geometric objects inherit all attributes from their parents, information about their generation history and their neighborhood.

The outline of the paper is as follows: In the next section we give a very short introduction into the basic ideas and advantages of the *p*-version of the finite element method. Section 3 describes the algorithms transferring the architectural model to a three-dimensional finite element model and in Section 4 a complex example is discussed.

2 A high order solid finite element formulation

In principle, the classical finite element method (*h*-version) is well suited to simulate 1-, 2- and 3-dimensional structural problems. Yet, it demands for element shapes having an aspect ratio not far from one, meaning that, for example, three-dimensional elements should have element edges of more or less equal size. If this restriction is violated, low accuracy or 'locking' may occur. As a consequence, a discretisation of thin-walled structures like slabs, plates or shells with hexahedral tri-linear elements would demand for a very large number of degrees of freedom, as the size of the elements would be limited by their (small) thickness. Therefore, dimensionally reduced models like Reissner-Mindlin-plates or Naghdi-shells are used in most practical applications. As, on the other hand, slabs or plates are strictly three-dimensional geometrical objects in an architectural building model, a transfer from the architectural to the classical structural model requires reduction of dimension, being error-prone and (to the knowledge of the authors) not being performable automatically in general.

As an alternative to dimensionally reduced formulations for an approximation of thin-walled structures, we apply a strictly three-dimensional continuum approach of high order. The *p*-version of the FEM (Szabó 1991) offers a consistent and accurate way to implement solid elements having a very large aspect ratio (up to a few hundred). Due to the use of the blending-function method (Szabó 1991), the geometry of the structure may be accurately discretized. The implementation is based on a hexahedral element, allowing for an anisotropic Ansatz of the displacement field. The polynomial degree of each separate component of the displacement field can be chosen individually and may also be varied in the three local directions of the element. This anisotropic Ansatz allows the efficient computation of three-dimensional plate- and shell-like structures. A transition from thin- to thick-walled constructions is thus possible without the necessity to couple models of differing dimensions and without imposing any restrictions on the (three-dimensional) kinematics of the structure. The underlying hierarchic finite element concept has several advantages over classical dimensionally reduced approaches. The assumptions of the displacement field in thickness direction are introduced during the discretization and not prior to that as it is done in the semi-discretization of classical shell elements. Therefore the model error, related to every plate or shell theory, turns into the discretization error of the strictly three-dimensional approach, which can even be controlled by adaptively increasing the polynomial degree in thickness direction. In a similar way, the polynomial degree in in-plane can be adaptively controlled (Rank 2004).

The element formulation used here also allows for nonlinear computations. Different model problems, like linear elasticity (Düster 2001, Szabó 2003), thermoelastic problems (Düster 2002/2), elastoplasticity (Düster 2002/1) and also hyperelasticity (Düster 2003) have been considered.

3 From geometric models to the finite element analysis

3.1 Model transformation

Exchange of building model data in the construction and facility management industries is standardized by the *International Alliance for Interoperability* (IAI), providing its *Industry Foundation Classes* (IFC). The goal of this product model standard is to define an integral, object-oriented and semantical model of all components, attributes, properties and relationships of and within a *building model*. The IFC product model is specified using the modeling language EXPRESS, which has been used to define STEP based product models within ISO 10303 before. Since 2002, the current release IFC 2.x is certified as ISO/PAS 16739 standard. For further information refer to (IAI 2003) and the references therein.

Although this building model stores the complete geometry of a construction, it is not directly adequate for numerical simulation, as it only implicitly describes the topology and the mutual connections of different structural components. The IFC-standard, for example, allows to define a room by its floor plan and corresponding heights, and openings for windows in a wall by their relative position to an 'anchor point'. To make the topology and the connections explicit, we therefore define further representations of the building's geometry. First we derive from the building model (IFC) a boundary representation model (BRep-model) with attributed objects. This is done by using the IFC-Eurostep Toolbox (Eurostep 2000) in combination with the geometric modeler ACIS from Spatial Corp. (ACIS 2004) to perform the transformation into the BRep-model. As a second step, the geometric model is decomposed into a so-called *'connection model'*. This consists of *coupling objects*, being bodies at all location where structural components are in plane contact, and *difference objects* only being in contact with other difference objects at nodes or along common edges.

We assume that after decomposition, coupling objects possess *hexahedral structure* while difference objects can be described by *sweeping of a planar polygonal domain*. It should be mentioned that this approach does not aim at meshing general spatial structure into hexahedral elements but is capable of decomposing objects being related to typical building elements, like plates, beams, columns and slabs.

3.2 Connection model definition

Consider a consistent geometric building model $\Omega \subset \mathbb{R}^3$ as a set of one or more BRep bodies.

Without given a precise definition of consistency, we assume that the building model is free from 'gaps' and there are no 'overlaps' of building elements. We distinguish between the following types of intersection of objects (Figure 1):

- *Type NEF*. The intersection of objects with adjacent faces consists of nodes, edges and faces.
- *Type NE*. The intersection of objects with adjacent edges consists of nodes and edges.
- *Type N*. The intersection of objects with adjacent nodes consists of nodes only.

Objects can thus be characterized according to their intersections with other objects. Based on their different semantics, they are partitioned into a set of *coupling objects* M_K and into the set of *difference* objects M_D (Figure 2).

Each coupling and difference object is itself a closed BRep object being described by nodes, edges and faces. Intersection between difference objects are of type *N* or *NE*, between coupling objects of type *N*, *NE* or *NEF* and between difference and coupling objects of type *N*, *NE* or *NEF*.

The set of coupling objects M_K are further partitioned into the set of *coupling objects of the original model* M_{K1} and the set of *coupling objects of the connection model* M_{K2}. The decomposed geometric model, the *connection model*, contains the aggregated set of objects M_C. We define:

$$M_{K1}, M_{K2} \subseteq M_K, \quad M_{K1} \cap M_{K2} = \varnothing \;\text{ and }\; M_{K1} \cup M_{K2} = M_K \subset M_C \tag{1}$$

$$M_K \cap M_D = \varnothing, \quad M_K \cup M_D = M_C \tag{2}$$

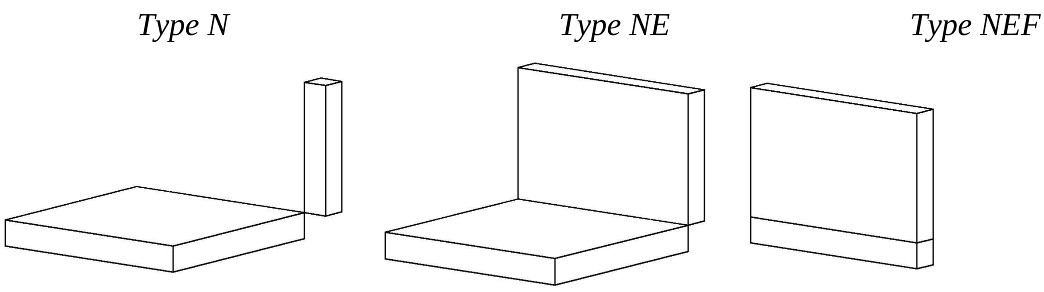

Figure 1: Intersection types N, NE and NEF

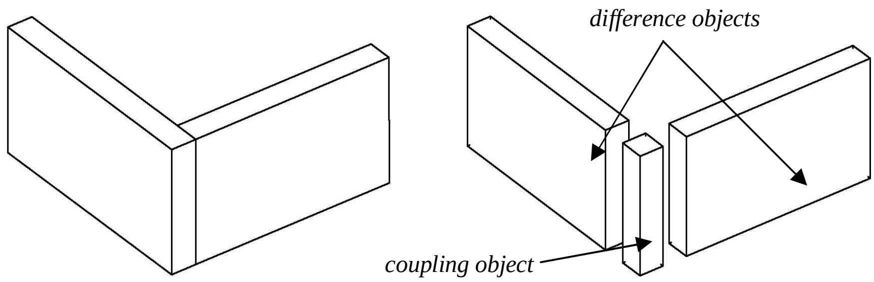

Figure 2: Connection model with coupling and difference objects

3.3 Decomposition algorithm

We consider a geometric building model $\Omega \subset \mathbb{R}^3$ consisting of a set of n BRep-objects ω_k:

$$\omega_k \subseteq \Omega, \quad k = 1, \ldots, n \text{ and} \tag{3}$$

$$\bigcup_{k=1,\ldots,n} \omega_k = \Omega. \tag{4}$$

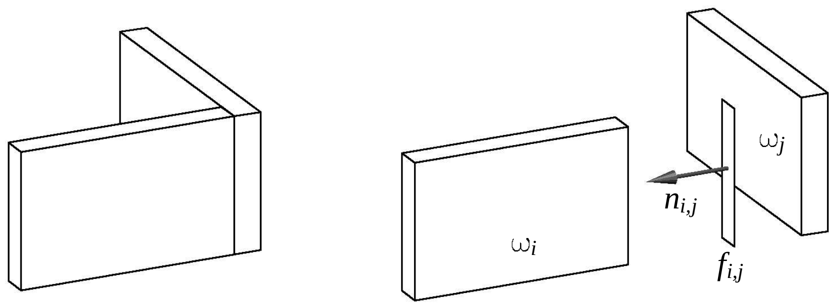

Figure 3: Intersection face $f_{i,j}$ with normal vector $n_{i,j}$ of two objects ω_i and ω_j

According to Figure 3, for each pair of objects ω_i and ω_j of this set, for which an intersection face exist, we run the following algorithm using the Boolean operations *intersection* $\cap_b$ and *difference* $\setminus_b$ resulting in the connection model with the above described objects:

1. Create imprint face $f_{i,j}$
2. Create normal vector $n_{i,j}$
3. Create copy ω'_i of ω_i
4. Move ω'_i along $-n_{i,j}$ by Δd
5. Create copy ω'_j of ω_j
6. $a_1 := \omega'_i \cap_b \omega'_j \subset M_{K1}$
7. $d_1 := \omega_i \subset M_D$
8. $d_2 := \overline{\omega_j \setminus_b a_1} \subset M_D$

After decomposition, coupling objects possess hexahedral structure while difference objects are assumed to be obtained from sweeping two-dimensional polygonal domains.

Example: To demonstrate the basic idea, Figure 4 to Figure 6 show a set of objects and their decomposition into a connection model. Knowing about all object relations, for each pair of objects imprint-faces are generated and the model is decomposed. Accordingly, the algorithm is continued recursively.

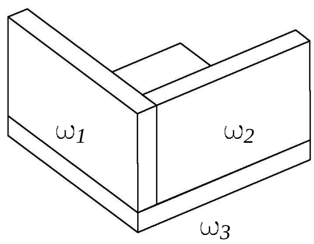

Figure 4: Configuration Ω with the objects ω_1, ω_2 and ω_3

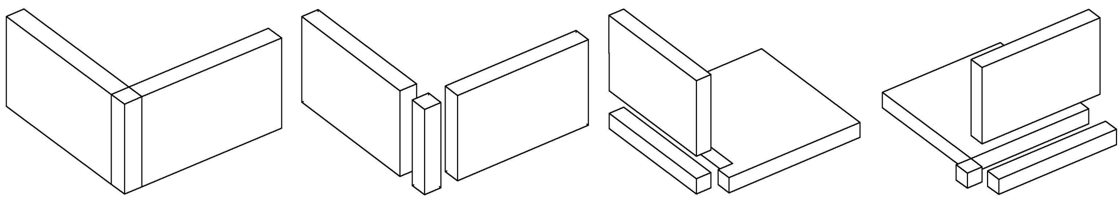

Figure 5: Recursive application of the algorithm

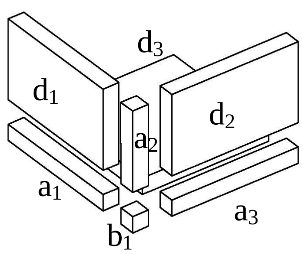

Figure 6: Connection model with coupling objects a_1, a_2, a_3, b_1 and difference objects d_1, d_2, d_3

3.4 Automatic mesh generation with hexahedral elements

Initial point of the mesh generation is a model which is decomposed by applying the algorithm of the preceding section. Coupling and difference objects are meshed in an explicitly given sequence and with type sensitive meshing algorithms. We use either elementary three-dimensional meshing macros or hexahedral meshes obtained by sweeping 2D quadrilateral meshes. In a first run (steps 1 and 2), a reasonably refined mesh for each (separate) difference object is defined. Most crucial in meshing is yet the question of generation of compatible elements. This demands for a 'second run' in the following steps 3 to 8. Only when the position of nodes, edges and faces of hexahedra on coupling objects is inherited to their adjacent difference objects, elements without hanging nodes can be guaranteed.

The meshing process is executed in the following steps:

1. Definition of refinement-macro around columns (see 'office tower' in the following section).
2. Meshing of objects d_k of M_D with a 2D quadrilateral mesh generator. Afterwards extrusion of the 2D elements in the third direction.
3. Assignment of the discretization of objects d_k to the adjacent objects a_i via common faces.
4. Refinement of the objects b_j of M_{K2} of reentrant corner.
5. Refinement of object a_i of M_{K1}. This has to be done under consideration of the first meshes of *all* adjacent objects d_k for a compatible discretization.
6. Deletion of first meshes for all d_k.
7. Assignment of the discretization of objects a_i to the adjacent objects d_k.
8. Second run of meshing for all objects d_k, but now with regard to the already given discretization of the region boundary.

As an example for the meshing algorithm, the following sequence of Figures shows the major steps for a simple box model.

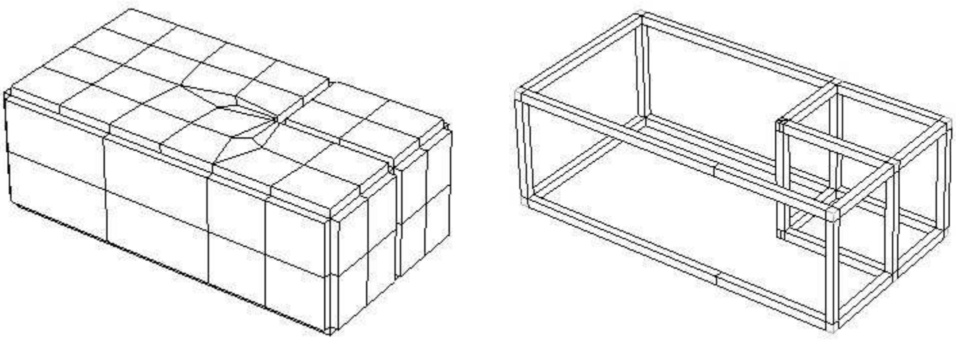

Figure 7: Model with free-meshed difference objects d_k (left-hand side) and refined coupling objects b_j (right-hand side)

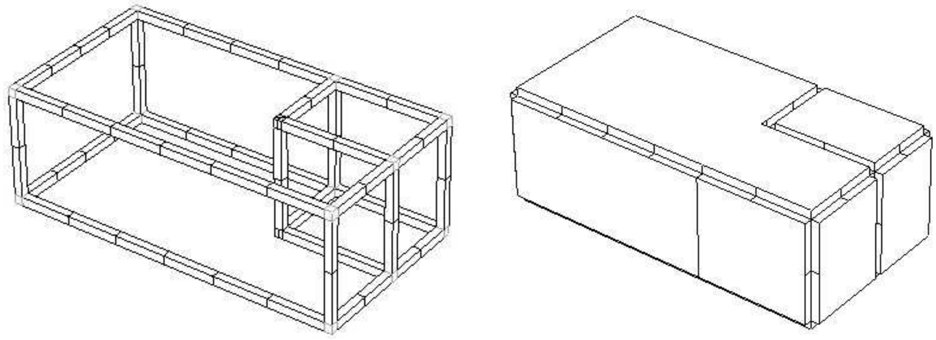

Figure 8: Model with refined coupling objects a_i (left-hand side) and assigned discretization onto the difference objects d_k (right-hand side)

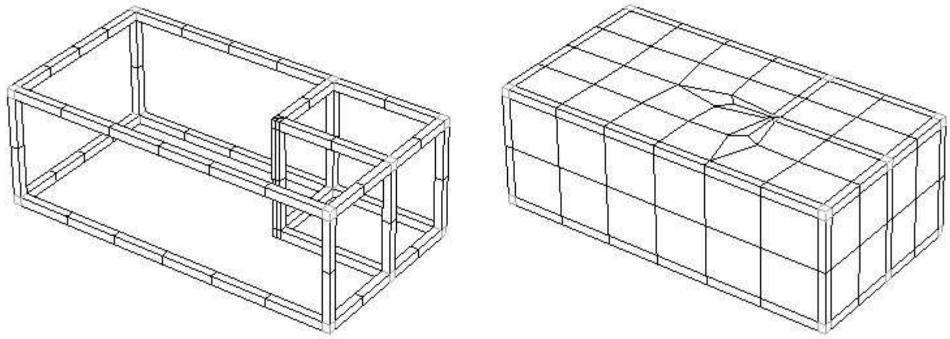

Figure 9: Model with refined coupling objects a_i (left-hand side) and aggregated hexahedral objects (right-hand side)

4 A complex example

Figure 10 shows a realistic office building with the dimensions of 40×30 meters in the ground view. The building is constructed by reinforced concrete and consists of two massive inlying building cores, six floor plates and supporting columns. For the structural analysis, the curtain wall is not considered. Dead load, a vertical live load and horizontal wind load being imposed via the curtain wall onto the faces of the slabs is taken into account.

On the right-hand side of Figure 10 the decomposed structure without the curtain wall is shown. On the top of the building the position of the coupling objects being generated because of the connection of the inlying building cores and the top level slab as well as the coupling objects caused by the connection to the columns can be identified. Figure 11 shows on the left the meshed structure consisting of hexahedral elements only and on the right a displacement plot after the structural analysis with the *p*-version of the finite element method.

5 Conclusion

We have presented an approach, simplifying the transfer from the product model to the finite element analysis model. This approach allows to model civil engineering constructions in a strictly three-dimensional setting. It releases the engineer from the task to transfer three-dimensional design models to dimensionally reduced finite element discretizations. The whole iterative design process is therefore carried out in three dimensions and both design and analysis are based on the same geometrical model, reducing sources of inconsistencies considerably.

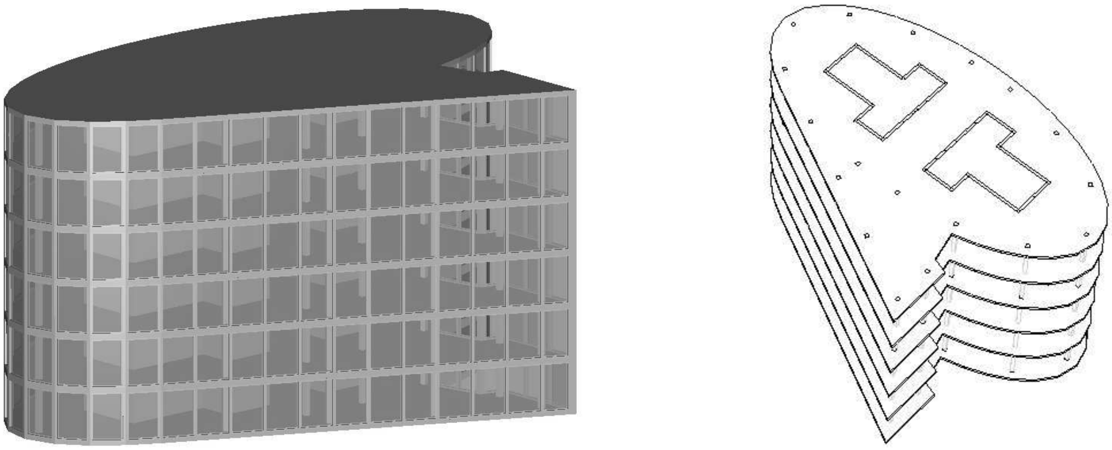

Figure 10: Model of the office building (left-hand side) and the decomposed model (right-hand side)

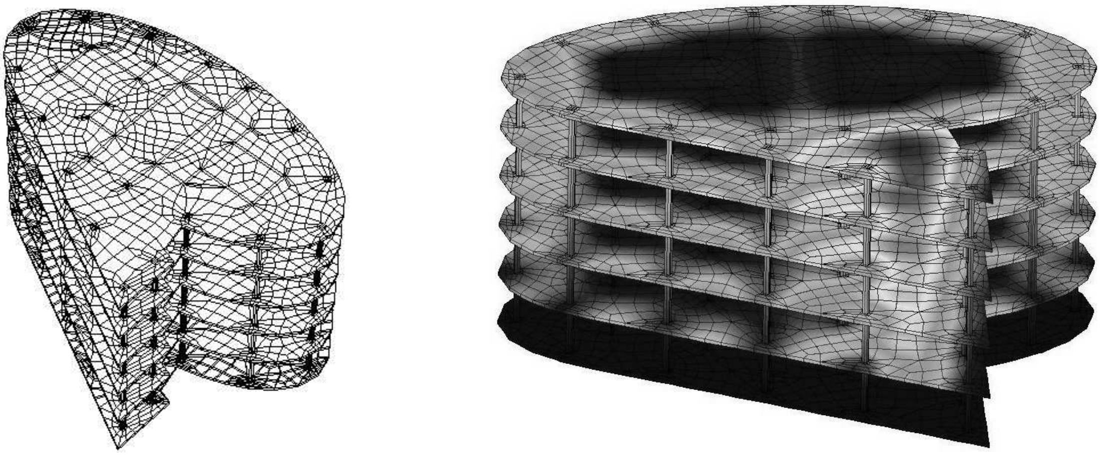

Figure 11: Meshed structure of the office building (left-hand side) and the plot of vertical displacements (right-hand side)

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