

Different Modelling Approaches to Coupling Wall and Floor Panels within a Dynamic Finite Element Model of a Lightweight Building

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Abstract

This paper presents an investigation of a skeleton based coupling technique used for the assembly of different modules, *i.e.* walls and floors, in a modular finite element model. For simplicity the skeleton is introduced in the intersections of the panels. In this way all panels can be constrained to the global skeleton, leading to a removal of the constrained degrees of freedom (DOFs) in the individual panels. This artificial skeleton will inevitably influence the surrounding structure as the skeleton will be a physical part of the model. This issue is addressed. Furthermore, decoupled pseudo-modes of the skeleton are discussed and analysed.

Keywords: modular, lightweight, building, vibration, panels, coupling, finite element method.

1 Introduction

In [1] written in collaboration with the co-authors of this article, a parametric modular finite element model is presented. The core of this modular finite element model consist of connecting the different modules, *i.e.* walls and floors, to each other in a rational manner, beneficial for both the accuracy and with as many applications as possible. The coupling method of the structural panels in this modular finite element model is discussed and evaluated. The model will be most applicable, if the connections can simulate fixities as well as pinned connections and, ideally, transitions. This is all desired for as few numerical calculations as possible.

The model is developed in ABAQUS [2]. It is investigated how the panels are connected in an efficient way, where the setup of the model as well as the accuracy of the results is optimized. In this connection it is also desired to have easily accessible and readable results, which involves the introduction of an artificial skeleton and hereby

retaining the individual panels in the global model. This leads to the need of an auxiliary skeleton, connecting all the wall- and floor panels, due to the applications and limitations of the constraining tool in ABAQUS. This gives rise to some problems, as the introduced skeleton will influence the surrounding structure. In essence the purpose of the skeleton is to connect intersecting panels along common interfaces. But as the skeleton is a structure itself, it will have a physical mass and a corresponding stiffness to be included in the linear system of equations. This means that the skeleton will influence the structure with an increased overall stiffness. This influence is quantified and sought reduced.

The accuracy of the coupling system is measured by the ability to obtain Eigen frequencies in agreement with models, where no skeleton is used. This is investigated numerically by coupling two shell elements with altering coupling conditions.

In a modular building model consisting of several storeys, the response of some areas is inevitably of more interest than others. Therefore the possibility of increasing the accuracy locally by refining the mesh is investigated. This is done in a convergence study, where the convergence of a uniformly meshed model is compared with models with nonuniformly meshes. Here it is interesting to see if the results can be improved by refining the mesh locally or the results solely depend on the lowest common denominator. In this respect it is also worth mentioning that the skeleton for instance also may introduce pseudo-modes which represent some modes of the skeleton alone, if the mesh along the skeleton is more refined than the mesh along the edges of the panels. This issue is highly dependent on the coupling method as well as the mass of the skeleton and will be examined further later in this article.

2 Assembly of a modular building model

An example of this modular building which needs to be interconnected is shown in Figure 1, where a $2 \times 2 \times 2$ modular building is set up. The setup of the modular building model is described in Ref. [1].

The building is put together via a global skeleton connecting all floor and wall panels. The advantages as well as the drawbacks of this assembly approach alongside some alternatives are discussed and analysed throughout this paper. It is chosen to use a skeleton, to avoid two Slave (or Master) elements to be constrained to each other, see Section 2.3, as these setups are impossible to form at corners of a finite-element model in ABAQUS.

The skeleton is made of beam elements, located in the intersection between the panels (walls and floors). By choosing a small beam profile (e.g. 1mm squared), the effects introduced by the presence of the skeleton will be reduced, while the advantage of the well-defined geometry is retained. In Subsections 2.1 and 2.2, two potential alternatives to the skeleton approach are described. Here the applications as well as limitations, leading to the choice of the skeleton approach, used throughout the article in Section 3 and 4, are described.

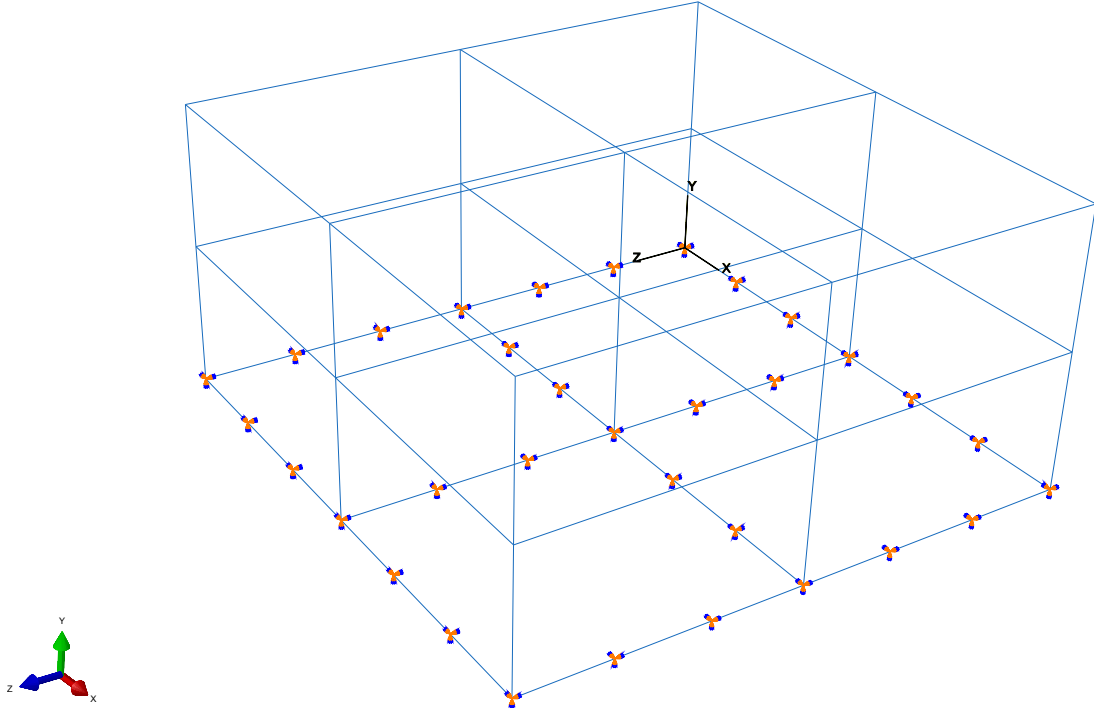


Figure 1: Layout of a $2 \times 2 \times 2$ module building. The skeleton is plotted in blue. The orange and blue arrow heads indicate fixed (retained) translational and rotational (DOFs at the foundation).

2.1 Shells connected via constraints

The simplest way of coupling multiple shells in ABAQUS is by making *Tie Constraints*. These constraints are constructed by defining a master panel and a set of Slave panels. This constraint results in a removal of the DOFs on the Slave panel for every coincident node on the master panel. These coincident nodes are defined within a certain maximum tolerance criterion. All DOFs on the Slave panel, both translational and rotational, will be removed, if these DOFs exist on both the master and the Slave panel, creating a fixed connection [3]. In order to create a pinned connection, the rotational DOFs are left uncoupled.

When creating tie constraints at corners, the definition of the constraints in ABAQUS is however limited, as a Slave node of one tie constraint cannot be a Slave node of another tie constraint. This issue makes it impossible to tie more than two elements together at coincident nodes, when all Slave panels have to be tied together. This becomes a problem at corners, where three elements or more intersect [3], see Figure 2.

In the figure, the floor is selected as the master panel, which implies that the DOFs along the upper edges of the wall panels are removed. As a Slave panel cannot be used as a Slave panel twice, the two walls cannot be tied together, indicated by the red hatched area. As this coupling is not feasible for intersections consisting of more

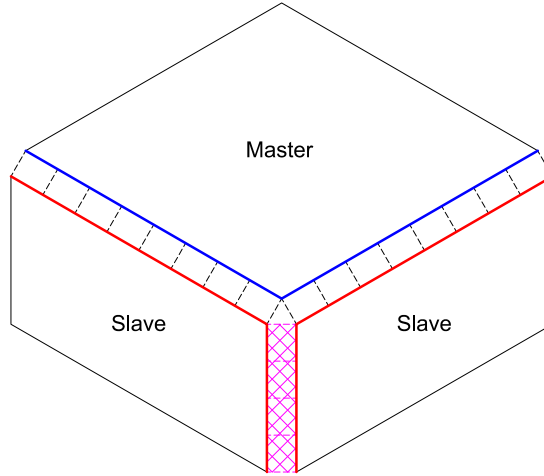


Figure 2: Master panel (blue): Floor; Slave panels (red): Walls. The dotted lines illustrate the constraints.

than two panels, the introduction of a skeleton is proposed, which would provide a convenient way for the coupling, as the skeleton will act as a one single master node set. Alternatively the entire geometry could be merged as discussed in Subsection 2.2.

2.2 Merged geometry

An alternative to the direct tie constraint approach discussed above is a fully merged geometry, where the panels are fixed to each other. Here the wall/floor panels will become one part in the merging process, which superfluous the constraints. The approach implies that all the included elements will be fixed together, eliminating the possibility of releasing the rotational DOFs. In this way it is not possible to model a pinned connection between the involved shells, which will limit the applications to fully fixed connections. This will however make the result difficult to extract and read, as the structure is not divided into the individual parts, i.e. floors, external/internal walls, et cetera.

2.3 Global skeleton

As discussed in Subsection 2.1 it would be preferable to create a skeleton to which all the panels can be tied, as the Master-Slave node problem is avoided, see Figure 3.

This is achieved by creating and merging a skeleton consisting of beams and columns in between the shells used for the skeleton. By applying relatively small beam profiles to the skeleton, the effects from the mass and stiffness gain due to the skeleton are reduced. Alongside the use of a small beam profile (compared to the dimensions of the real structure) a relatively low Young's modulus can be assigned. But care must be taken not to introduce singularities or other unwanted effects into the system of

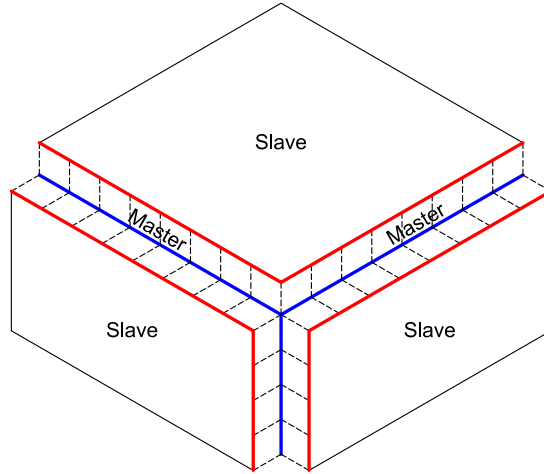


Figure 3: Skeleton used for the Master node set (blue), leaving all shells (floors and walls) as Slave panels (red). The dotted lines illustrate the constraints.

equations. The skeleton is then used as a Master node set, and the walls and floors are *Tied* to the skeleton.

3 Convergence analysis

In the convergence analysis, a simplified model is used to provide an easily comparable basis, as the model is built. The selected model consists of two panels connected at an angle of 90° and fixed at the two end edges. The panels are connected in three different ways. In this way, the approach where the skeleton is used, can be tested against the methods where no artificial skeleton is introduced.

- Model a, see Figure 4a, consists of the two panels, where the panels are constrained to each other via an ordinary “tie constraint” (no skeleton used).
- Model b, see Figure 4b, consists of the two panels which are merged into one part.
- Model c, see Figure 4c, consists of a skeleton placed in the intersections of the panels. The panels are constraint the the skeleton which acts as a Master node set.

The selected material properties for the panels as well as the fixed Poisson’s ratio for the skeleton are shown in Table 1. These values will be used throughout the article.

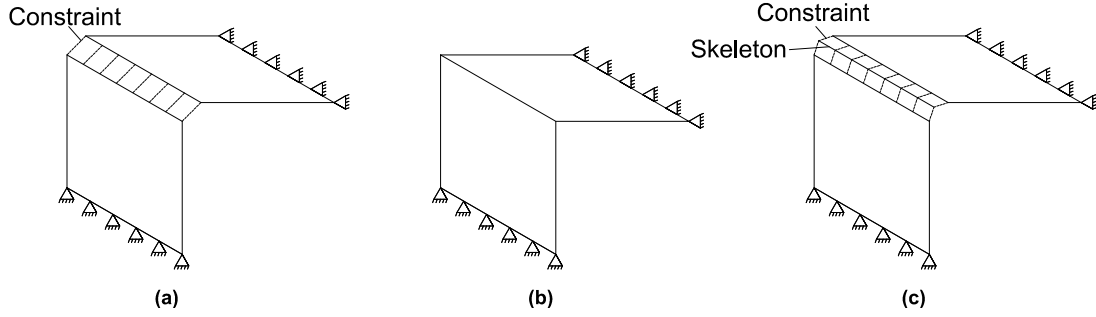


Figure 4: Model setup (a): Two panels constraint together, Model setup (b); Two panels merged together, Model setup (c): Two panels constraint to a skeleton/beam.

Material properties	Panels	Skeleton
Young's modulus	30GPa	-
Poisson's ratio	0.2	0.2
Density	2350kg/m ³	-
Thickness	0.1m	-

Table 1: Material properties for the panels (walls and floors), as well as the fixed value(s) used for the skeleton.

3.1 The influence of the skeleton

The introduction of the artificial skeleton will inevitable affect the behaviour of the building model, as the skeleton will be a part of the structure in the model. But as the skeleton is merely an aid to get a convenient way of applying the individual panels in the global geometry, the influence needs to be minimized. This is important, as the skeleton will not be present in the real world building, and hereby the effects of this skeleton will also be non-existing. The effects are minimized by choosing proper material properties for the skeleton.

The inclusion of the skeleton as a part of the structure provides an easy way of coupling the Master and Slave nodes of the structure, eliminating the need of coupling each individual node along the edges of the panels to the nearest intersecting neighbouring node. Because of this implementation of the skeleton, the skeleton needs to be given a certain mass, stiffness and physical dimension (i.e. a beam cross section), see Figure 5.

The inclusion of the skeleton will result in a stiffer structure and hereby introduce higher fundamental frequencies, if the beam profile and the stiffness of the beam are selected too high. However if the parameters are selected to low, there is a risk of introducing singularities in the system of equations.

It is found that test setups (a) and (b) (see Figures 4a and 4b), provide identical results and hereby equal frequencies for the individual modes. These are compared

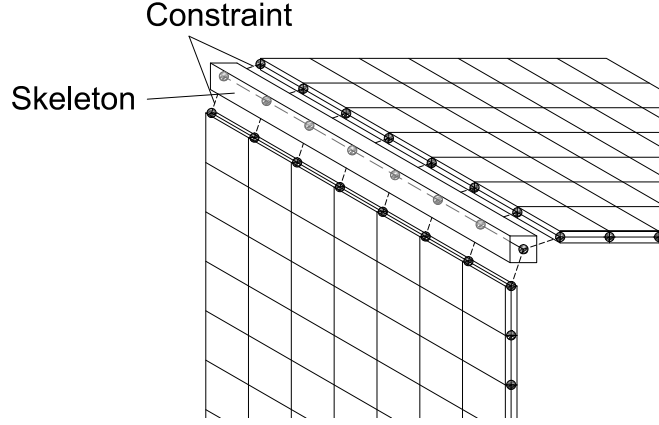


Figure 5: Beam at panel intersection. The panels are constrained to the skeleton illustrated by the dotted lines.

with the Eigen frequencies found in Model c (Figure 4c), where the skeleton/beam structure is present.

In Figure 6 the difference in Eigen frequencies in Model c are compared with those of Model a, with respect to both the beam dimension (profile size) as well as the stiffness of the skeleton. The material properties used in Figure 6 are shown in Table 1, except for the density which is kept constant at 1kg/m^3 .

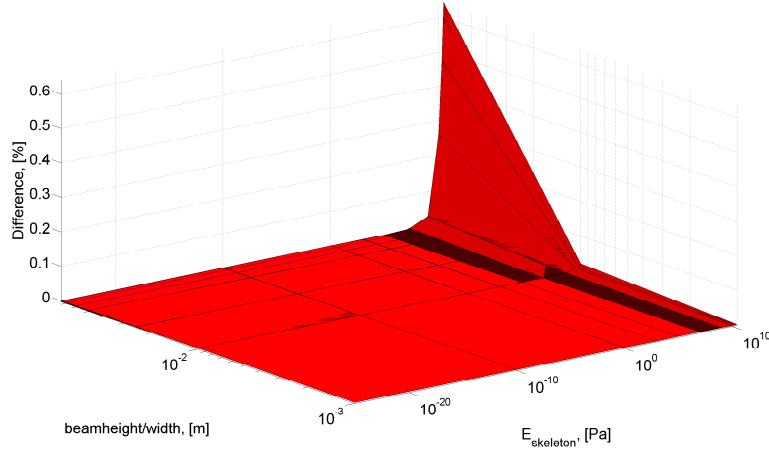


Figure 6: Percentage-wise difference in Eigen frequencies of the model including a skeleton (Model c) relative to the simple model (Model a & Model b). The maximum values for mode 1-20 are displayed. ($\rho_{skeleton} = 1\text{kg/m}^3$)

It is seen that the Eigen frequency does not vary for low values of both the stiffness and the beam dimension. For instance if the beam profile is selected to a square of $1\text{mm} \times 1\text{mm}$, the first 20 modes (up to 1300Hz) are not affected ($\ll 0.6\%$), if the

modulus of elasticity is kept below 1GPa, corresponding to a few percent of stiffness of the panels (3.3%).

It is chosen to use a square beam profile with the dimensions $1\text{mm} \times 1\text{mm}$. The corresponding stiffness of the skeleton therefore have to be below 1GPa as described above. As the skeleton will be a part of the final structure, the stiffness of the skeleton will influence the structure together with the density of the skeleton. It is important to tune these properties, in a way that no pseudo-modes are created, in which the skeleton will vibrate decoupled from the surrounding panels. As it is chosen to use a fixed value for the beam profile, the Eigen frequency of the skeleton it self, will be scaled by w (width of the beam profile), as the mass of the beam is scaled by the beam profile squared (w^2), and the stiffness is scaled by w^4 , via the second moment of area, $\omega = \sqrt{w^4/w^2}$. This can be used to avoid mentioned pseudo-modes discussed in Section 4.

3.2 Nonuniformly meshed panels

When tying the different shells together, it is important to obtain a continuous interface between the different shells to ensure reliable results. As the tie constraints are constraining the nodes together, this is most easily obtained by using the same mesh size across the entire model, in the shells as well as in the skeleton. This will however limit the applicability of the model, as it would be preferable to be able to look in detail at some parts of a building. Therefore it is investigated if the accuracy can be increased locally in the model, without refining the mesh everywhere.

Another problem, when using unequal meshes, which is defined by altering mesh refinements in the Master region (skeleton) compared with the Slave region (panels), is the risk of getting a distorted geometry, where the analysis is likely to fail. This holds true in particular for meshes, where the Master mesh in relation to the Slave mesh, is not scalable by an integer. The convergence of an unequally meshed geometry also needs to be tested, to see if a faster or slower convergence is achieved or to see if it is achieved at all. The layout of the test setup for this test is the same as used earlier in Section 3, with a load applied in the middle of the wall and a reference point in the middle of the floor, see Figure 7.

The convergence for unequally meshes models is analysed below. In Figure 8 and Figure 9, the Eigen frequency is plotted with respect to the mesh size in both the skeleton (Master) and the panels (Slaves). Likewise the displacements in the reference point is plotted for the same varying mesh size in both the skeleton and in the panels.

Figure 8 represent the first mode, while the 20th mode is shown in Figure 9.

It is here clearly noted that a faster convergence is obtained when the mesh size is the same in both the skeleton and in the panels. It would be a problem to refine the mesh locally as this will jeopardize the convergence of the entire model. This is especially a problem for Slave meshes which are more refined than the Master mesh in the skeleton. This of course depends on the individual mode shape, but the convergence is in general worse when the Master mesh lacks refinement. This could

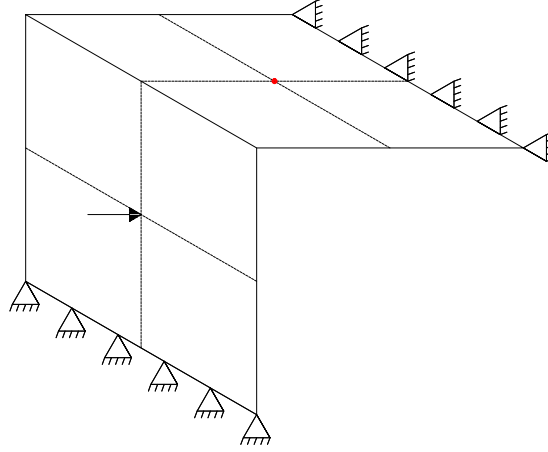


Figure 7: Test setup for the unequally meshed model. A unit load is applied in the middle of the wall, with a corresponding reference point in the middle of the floor.

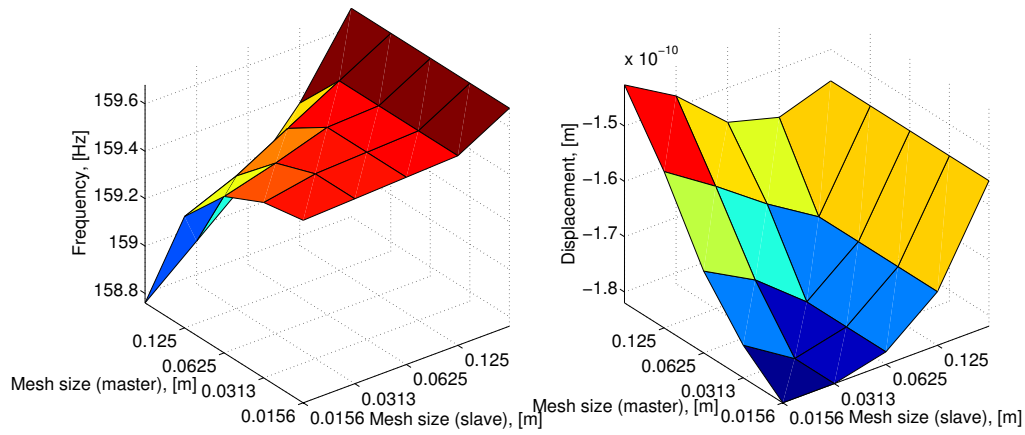


Figure 8: Eigen frequency for mode 1 with varying mesh sizes in the Master (skeleton) and the Slave (panels) region to the left. The corresponding displacements are shown to the right.

be due to the lack of conformity along the common boundary, where a lower number of DOFs, constraining the panels to the skeleton, is present. An example of a structure with relatively few DOFs along the Master skeleton is shown in Figure 10.

This unequal mesh results in a discontinuous structure along the skeleton, due to the less refined mesh along the skeleton. The coupling is particularly discontinuous when the mesh refinement is as diverse as in this example. It is noted that the Slaves (the panels) move freely between the nodes of the skeleton, and the structure is only intersecting at the nodes and not along the edges of the panels as intended. This results in poor conformity—especially at higher modes.

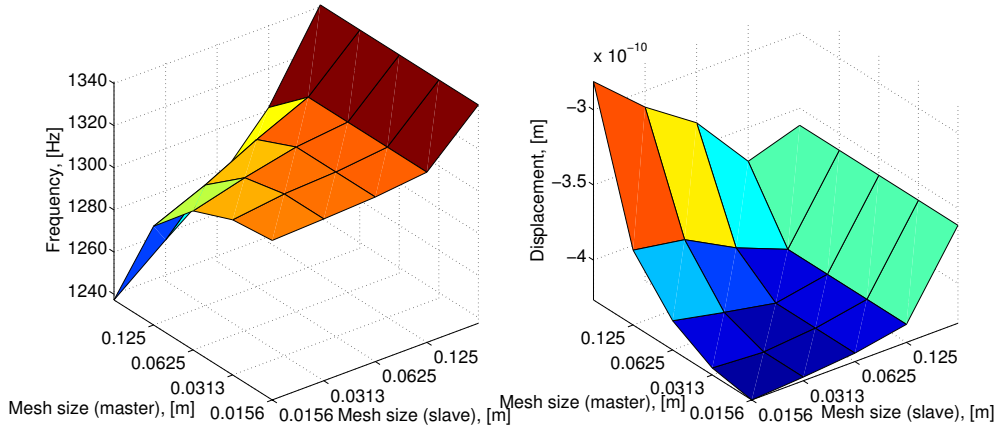


Figure 9: Eigen frequency for mode 20 with varying mesh sizes in the Master (skeleton) and the Slave (panels) region to the left. The corresponding displacements are shown to the right.

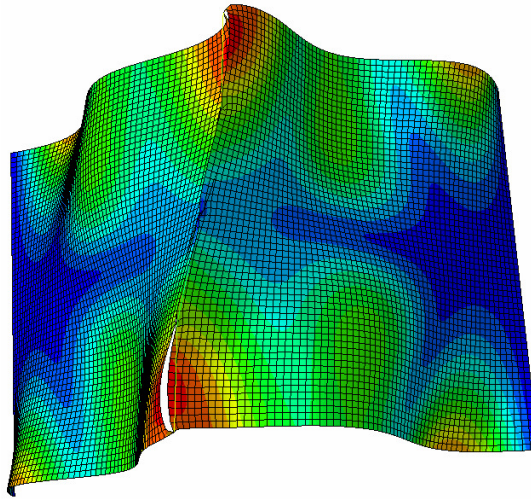


Figure 10: Eigen mode 20 with unequally meshed skeleton/panels. Master (skeleton) refinement = $1/2m$, Slave(panel) refinement = $1/64m$.

When the skeleton is less refined than the panels, the Eigen frequencies are found to be too low with deviations up to 20% (mode 2) for the first 20 modes. For instance 5% deviation can be found in Figure 8 for mode 1.

In Figure 11 the structure is shown with an equal mesh in the skeleton and the panels. It is noted that the structure is continuous in the intersection opposite to the case in Figure 10.

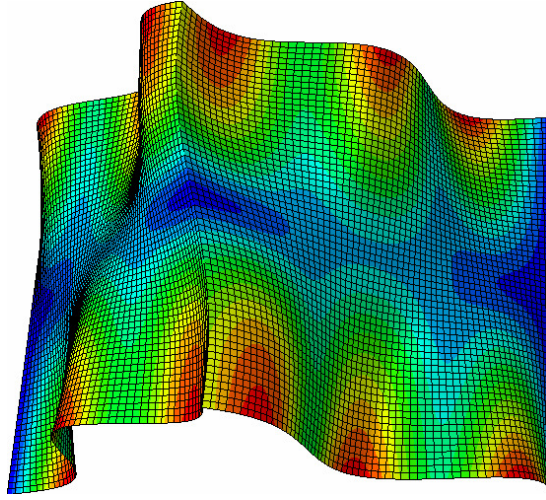


Figure 11: Eigen mode 20 with equally meshed skeleton/panels. Master (skeleton) refinement = 1/64m, Slave (panels) refinement = 1/64m.

4 Local deformation behaviour of the skeleton

When the mesh size of the individual panel is not equal to the mesh size of the skeleton, there are other issues to consider than a possible unfavourable convergence. When the mesh in the shells are more refined in the “weak” skeleton, there is a risk of getting a skeleton which will flutter, hereby creating pseudo-modes, as not all nodes along the beam axis will be supported by the much stiffer plates. A case like this is shown in Figure 12.

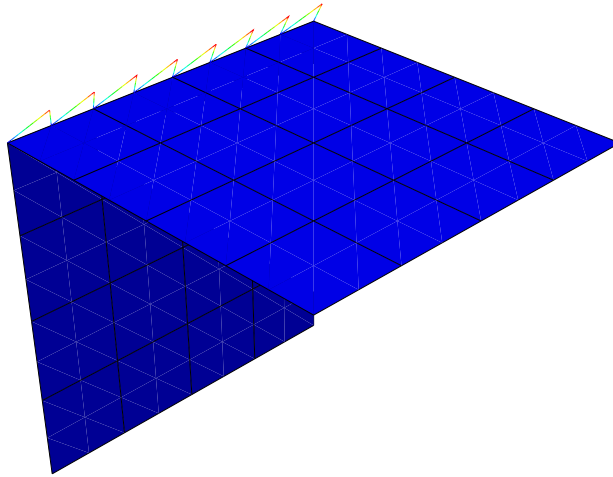


Figure 12: Example of a fluttering skeleton connecting two shells. Master (skeleton) refinement = 1/8m, Slave (panels) refinement = 1/4m, $E_{skeleton}=1000\text{Pa}$, $\rho_{skeleton}=1\text{kg/m}^3$, beam profile: $1\text{mm} \times 1\text{mm}$

It is shown that the skeleton is vibrating in a local mode where the interaction with the shells only occur through the constrained nodes. It acts as a beam supported only in the common DOFs, see Figure 13. As the material properties of the beam is subdued, a simply supported beam will be assumed, as this layout will have the lowest Eigen frequency, compared with for instance a fixed support.

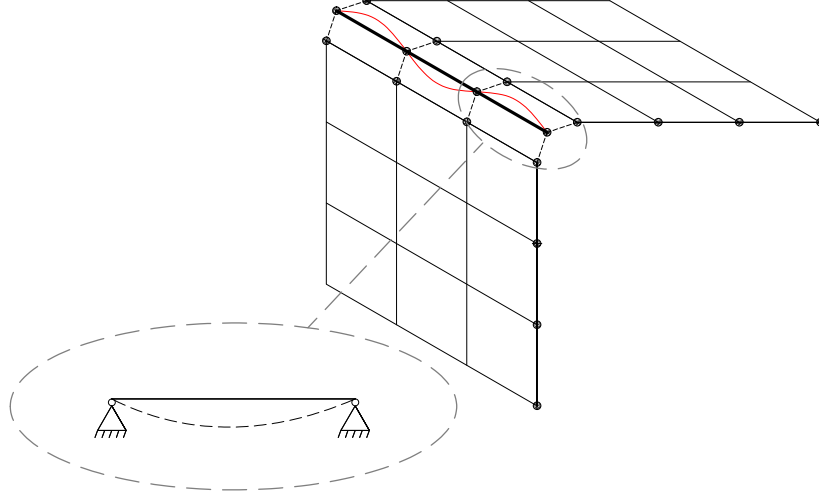


Figure 13: Local vibration of skeleton between two shells.

This behaviour needs to be avoided as these pseudo-modes are not found in the real structure. Hence they are undesired in the model. In Figure 12, the pseudo-mode is provoked by the low stiffness of the skeleton. But as discussed earlier, the stiffness is also desired significantly lower than that of the panels in the building. This means that the optimal interval for the stiffness needs to be found, to be able to keep the skeleton for the practical arrangement of the shells in a global grid and at the same time avoid undesired behaviour. This means that the stiffness of the skeleton needs to be tuned in a way, where the resonance is avoided within the desired frequency interval. For mode n of a beam with span length l , the natural frequency is given by [4], see Equation 1, where the Bernoulli-Euler beam theory is adopted, as the width and height of the beam profile is much smaller than the length of the beam.

$$f_n = \frac{C}{2\pi \cdot l^2} \cdot \sqrt{\frac{EI}{\mu}}, \quad n = 1, 2, 3, \dots \quad (1)$$

where C is a table value based on the n th mode shape ($C = 9.87$ for a simple supported beam, $C = 22.4$ for a fixed beam), and μ is the mass per unit length and EI is the bending stiffness, where I denote the second moment of area. By defining the desired frequency interval for which the model should provide accurate results and hence the maximum frequency of interest, it is possible to tune the parameters E , μ and the beam dimensions (I). This is done by selecting the parameters in a way, where

the Eigen frequency related to the first Eigen mode is kept above this interval. If the density is set to 1kg/m^3 and the mesh size set to $l = 0.25\text{m}$, Young's modulus has to be at least $E = 3.0 \cdot 10^7\text{Pa}$, according to the calculation.

$$E = \frac{f^2 \cdot l^4 \cdot \mu \cdot 2\pi}{C^2 \cdot I} = 3.0 \cdot 10^7\text{Pa} \quad (2)$$

where the skeleton cross section is assumed to have a side length of 1mm and $C = 9.87$ is employed, conservatively assuming the skeleton to be simply supported over each bay. This stiffness is much lower than the suggested value in Section 3.1, where a minimum influence (below 0.6%) was found with a stiffness of 1GPa . If it is desired to use the stiffness of 1GPa , the maximum frequency of interest can be increased to $\approx 600\text{Hz}$ instead of the 100Hz suggested in the calculation above, by doing the reversed calculation.

In principle it is also possible for the skeleton to rotate between the individual DOFs, as shown in Figure 14. But this mode, will in general occur at a higher frequency than bending of the simply supported beam and will hereby not be further discussed.

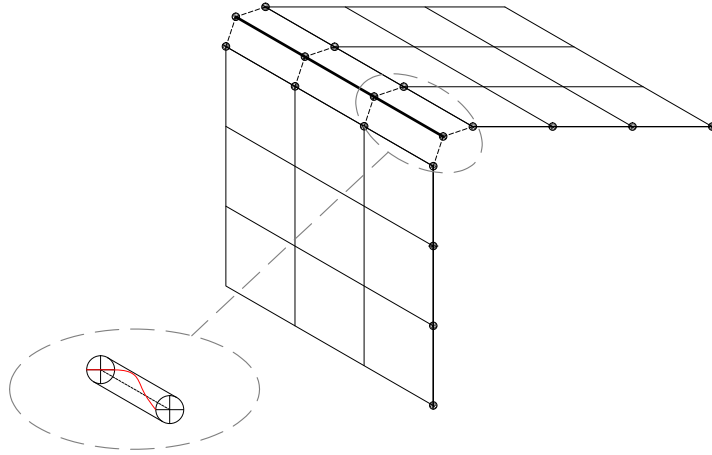


Figure 14: Local rotation of skeleton between two shells.

5 Conclusion

It is found that the introduction of an artificial skeleton in a parametric modular finite element model is feasible, which simplifies the setup of the model and greatly improves the readability of the processed data. To achieve undisturbed results, meaning results similar to a model where no skeleton is used, it is important to use a skeleton with subdued material properties, meaning a low stiffness and a low mass. On the

contrary these properties cannot be set too low, as this will introduce some pseudo-modes, leading to Eigen vibrations in the skeleton itself. This becomes a problem in particular, when the mesh of the skeleton is more refined than that of the panels, as the relatively soft skeleton is free to move in the non-constrained nodes. This issue can be averted by choosing equal mesh refinements in both the skeleton and the panels, which will furthermore ensure a converging model.

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