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A case study on the influence of multiscale modelling in design and structural analysis

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Abstract

The current paper discusses the role of multi-scale modelling within the context of design and structural analysis. Depending on the level of detail, a design model may retain, lose or enhance key information. The term multi-scale refers to the break-down of a design and analysis task into multiple levels of detail and the transfer of this information between models. Focusing on the influence that different models have on the analysed performance of the structure, the paper will discuss the advantages and trade-offs of coupling multiple levels of abstraction in terms of design and structure.

To illustrate the concept of multi-scale modelling, the prototype of a bridge structure that was realised making use of this information transfer between models will be presented. The prototype primarily takes advantage of the geometric and material stiffening effect of incremental metal forming. The local features of the formed panels guarantee a proper load transfer between the elements, otherwise impossible to achieve in the planar, underformed state of the aluminium panels. In terms of structural analysis, each successive level of detail dramatically increases the computational effort required to assess the performance of the structure. By adopting the multi-scale modelling approach, the level of model refinement can be adapted to the requirements of the analysis and therefore relieve the simulation complexity especially in the early stages of design.

Keywords: multi-scale modelling, design, structural analysis, metal forming.

1. Introduction

Most physical phenomena can be described at different scales of resolution. Depending on the level of detail, certain aspects may lose relevance as others gain importance according to the specific scale of observation. In general, at higher scales certain abstractions can be operated that simplify the description of the phenomena under examination. These simplifications rely on observations at a lower scale along with the individuation of recurrent patterns and their formal description. These descriptive frameworks are then employed at the macroscale to model the behaviour of the phenomena and simplify the complexity of the system’s model. It could well be possible to model a whole bridge at atomistic level, but the complexity arising by doing so would not be justified by the added insight on the global behaviour of the structure. Taking into account the explicit microstructure at the coarse scale model is practically not feasible due to the prohibitive computational cost that it would lead to. The reduction of computational models to simplified versions is typical in science and engineering. The phenomena that rule the behaviour of the system at a lower scale of observation are normally safely disregarded. Nonetheless, in certain situations a concurrent modelling approach at multiple scales might be necessary to correctly describe the object of study. For this reason, a transfer of information must then occur at different levels of resolution to achieve the best trade-off between scales of observation.
Modelling approaches that actively rely on the exchange of information between different levels are termed multiscale. They originate on the base of the following observations: 1) that no single model or framework is adequate on its own to capture the full behaviour of a system, since the information and models that we have about the world are partial and bounded; 2) that modelling efficiencies can be gained by exploiting different levels of resolution; and 3) that high resolution models quickly becomes intractable at larger scales (Elliot [1]). Multiscale approaches assemble a multiplicity of models, each capable of describing an important feature using a particular framework. By transferring information between frameworks, these models are linked together so that the output of a given model becomes the input for another. Multi-scale modelling is therefore the identification and construction of suitable models and frameworks, together with the application of modelling techniques that relate or ‘bridge’ these models and frameworks (Elliot [1]) by coupling together different kinds of description. Multiscale models aim to describe a problem by separating it into discrete models, typically of different type and nature. They leverage that, for some applications, a model does not require the full complexity of the object. Each model addresses a particular feature of the design problem and can therefore focus exclusively on the correct representation of that specific feature. These models parameterize one another, either sequentially or simultaneously. A key concern is therefore those techniques which enable the information generated within each of these models to flow to others.

In engineering, and especially material science, multiscale models have been widely developed to capture the physics of microstructures to be able to efficiently predict the macroscopic behaviour of materials. Identifying the relationships between microstructure and macroscopic properties is an essential problem in material science as well as computational mechanics (Nguyen et al. [2]). Multiscale methods have been successfully employed in the simulation of composite structures, masonry, fluids, polymers and more. Such models are well suited in the case of heterogeneous and multiphase materials. The transfer of information between levels of observation typically occurs through numerical and computational homogenization methods. Homogenization is a method to determine the properties of a heterogeneous material at microscale, thereby allowing one to substitute this material with an equivalent homogeneous material or its descriptive information. Mainly used and developed in the field of material science, multiscale approaches are also attractive in other research contexts where multiple levels of resolution are involved in the analysis of the system.

Modelling in architecture is a typical example of hierarchical organisation of multiple scales that focus on one level at a time, gradually refining and adding detail from the larger to the smaller scale. The exchange of information between scales typically follows a simplified process, as the relationships are often linear among multiple levels of design. Architectural structures can be thought similarly: as nested organizations from which features, behaviours and properties emerge based on interactions across scales and systems (Nicholas et al. [3]).

Within architecture and structural design, one approach to multiscale modelling is to link a macro scale structural domain with a micro scale material domain. With either design generation or optimization as a goal, each level is varied so as to achieve a specific global effect. In the simplest case, this involves the iterative solution of one problem at the macro level (stability, for example) and several problems (which together inform the best local configuration) at the material level (Coelho and Guedes [4]). Some multi-scale models, including the approach described in this paper, include an intermediate meso scale level, in this case related to an architectural component and its detailing. But because the type and level of detail of information is different for the different levels of description, multi-scale models can easily be constrained by the need to translate information. For this reason, bridging techniques and communication techniques which translate, coarsen or refine information as they pass it between models are central to the multiscale modelling process. The mesh-based techniques described in this paper directly address this issue.
2. Case study: A Bridge Too Far

Thin panelised metallic skins play an important role in contemporary architecture, often as a non-structural cladding system. Strategically increasing the structural capacity of this cladding layer can offer significant savings for secondary and primary structural systems, but requires a modelling approach that guards against instabilities due to buckling at three distinct scales: buckling of the structure, buckling within panel elements, and buckling and tearing that can occur during the sheet forming process itself. This deep entanglement of macro and micro necessitates a multiscale approach. The case study discussed in the following paragraphs made use of multiple modelling scales to handle the increasing geometric complexity arising at higher levels. The structure consists of 51 unique planar, hexagonal aluminium panels, arranged into an inner and outer skin (Figure 1, Figure 2). The thickness of each panel varies locally, though it is at maximum 1mm thick. Excluding buttresses, the bridge spans 3m and weighs 40kg. Geometric features for resisting local footfall, buckling within each panel and structural connections – for managing shear forces across inner and outer skins – are produced through the custom robotic forming of individual panels.
The computational design approach uses a data tree structure to allow different computational operations including shape discretization, planarization, structural analysis, generation of rigidisation patterns, calculation of material properties, and optimization (Figure 3). These operations occur on the scale that is best suited or most efficient. A particular class, the HNode Class (Nicholas et al. [5]), was developed to connect these operations by creating and supporting bidirectional information transfer across data trees. This process happened at the lowest level of the tree, and is passed to a medium level resolution to inform the structural analysis. An example of downstream data propagation is the distinction between panels and seams. The bidirectional workflow tied multiple scales together in a consistent and manageable way. Ability to process and reference data in parallel to other levels made an element on one level aware of information at any other level of the tree. This enabled adaptation of any particular element based on higher or lower level information within an automated feedback loop, which includes fitness criteria from multiple scales of the model.
This project used robotic Incremental Sheet Forming (Jeswiet et al. [6]) to introduce rigidising and connection geometries into a panelised structure (Figure 4). The Incremental Sheet Forming (ISF) method imparts 3D form on a 2D sheet, directly informed by the 3D CAD model. A simple tool facilitates mould-less forming by moving over the surface of a sheet to cause localized plastic deformation. In this research, a double sided robotic approach was used that supported forming out of plane in opposing directions (Figure 5) (Nicholas et al. [7]). Geometric features that locally stretch the sheet out of plane increase structural depth, prevent lines of bending, and also provide architectural opportunities for connection and surface expression. Depending on the geometric transformation, properties are locally introduced into the material to different degrees, according to the depth and angle attained. At the material scale, local thinning of the stretched metal can lead to buckling or tearing when approaching zero thickness. The metal also undergoes cold working during the fabrication process, introducing local variations in hardness and yield strength. Aluminium 5005H14 was chosen as it provided a good balance between formability, forming speed, initial thickness and initial hardness.

3. Structural analysis

Extensive analysis accompanied the development of the bridge to assess its main features and global structural behaviour. As the modelling approach was mesh-based since the early stages of design, it made sense to employ the same base geometry to perform in parallel the structural analysis. In this way, a direct exchange of information between the architectural development and the structural analysis was established. The same models could be easily transferred between domains and be used directly without further required adjustments. For this reason, the usual pre-processing steps for Finite Element Analysis, namely the meshing of the continuous surface elements, could be skipped. Besides the immediate consequence of time saving, the possibility of working on the same geometrical model meant that a direct feedback between the architectural and the engineering working environments could be established without further manipulation of the input data. By doing so the input for the structural analysis corresponded to the output of the architectural design. In turn, the results of the structural analysis could be fed directly into subsequent design iterations of the bridge. The seamless exchange of information enabled the efficiency of the process, therefore saving time and computational effort during the development of the design.
3.1. Information flow and scale aspects

Despite the advantages mentioned in the previous section about the fusing of the architectural and structural models, the extreme level of detail of the highest mesh hierarchy posed an inherent problem for the agile analysis of the bridge. The third and highest level of mesh refinement quickly approached a number of elements which became intractable for preliminary structural analysis iterations. The model in Figure 5 shows the level of mesh detail that was used during the development of the project for the assessment of the structural behaviour. The model iteration displayed in Figure 5 corresponds to the second level of mesh refinement out of three total levels that were employed during the development of the prototype. Compared to the full resolution mesh, at this scale many geometric features were inevitably lost. As can be seen in the model above, the rigidisation pattern of each panel is only slightly outlined. The principle characteristic and main feature that donated stiffness to the panels and the global structure was therefore erased from the model.

In Figure 6 an analysis of individual panels at each level of resolution was conducted to evaluate the trade-off between the different models. The panels are analysed under self-weight and the deformation is displayed with a 300x magnification factor. Each panel is simply supported around the edges and is modelled with the same 5005-H14 aluminium material of the bridge. The aluminium has a stiffness of 69000 MPa for a specific weight of 27 kN/m$^3$. The analysed panels were part of the bridge’s deck and measure roughly 0.5m x 0.7m. From the front view and perspective, the strong influence that the rigidisation pattern has on the stiffness of the panels can be noted. In the third iteration of refinement the deflections of the panel are noticeably less visible in comparison to the previous two levels. This suggests that the stiffening effect of the pattern is not entirely negligible when evaluating the global performance of the structure. At each level of refinement, the analysed behaviour of the bridge changes dramatically, as the bending stiffness of the panels increases exponentially with respect to the geometric details embedded in the mesh model.
The compromise between accuracy and agility of analysis is extremely relevant in cases like this one. The trade-off operated by over-simplifying the computational model may not be adequate when the estimation error overwhelms the advantage of speed. Although the choice that was made in the development of the prototype favoured a safe approach by underestimating the stiffness of the panels, it has been shown that the geometric stiffening effect of the incrementally formed pattern is not negligible. The test case discussed here suggest that other methods should be sought that ease the transfer of information between the design and structural domain. A possible approach that lends itself well to this type of design investigations would be homogenisation techniques that were briefly introduced at the beginning of the paper. Rather than approaching the problem in a brute-force manner by feeding the raw mesh data into the structural analysis, the stiffness of single pattern portions could be evaluated beforehand and used as numerical input for the local stiffness of the individual finite elements. In this way, the bulk of data can be reduced to a single piece of information rather than having to deal with an explicit and heavy description of geometric features.

4. Conclusions
This paper discussed the application of a multi-scale modelling approach developed for the design and fabrication of a prototypical bridge structure. Different levels of model resolutions offered a seamless transfer of information between the modelling frameworks. The multiscale process was tested and put into practice within the design environment of the bridge. The information transfer between the design environment and the structural analysis ran through the same mesh models, therefore reducing the need of translating working files from one platform to the other. Nonetheless, the high level of resolution of the design working models rendered the structural calculations not efficient enough for quick design explorations. Investigations on the mesh sensitivity showed that at lower levels of detail the accuracy of the simulation was partially compromised. Drawing from existing research in the field of multiscale modelling for material simulation, further developments and ongoing research will be focusing on the implementation of alternative methods of information transfer such as homogenisation techniques. In this way, an efficient and seamless link between design and structural simulation could be achieved.
References


