Modelling Stone Decay

Computer aided behavioural analysis of complex physical systems applied to stone decay in monuments

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Abstract

The increase in atmospheric pollution has accelerated the decay of many historic monuments. Computer modelling is an appropriate tool to understand and analyse this decay process. The problem of developing a stone decay model is one of complexity. A model for stone decay on the scale of a complete monument requires sufficient *scope* to integrate many different decay mechanisms and sufficient *depth* to support detailed analysis of such mechanisms in certain critical sections of the monument. We suggest that the intractabilities of scale and scope may be overcome through intelligent use of abstraction and simplification. We propose a model architecture which allows successive refinement of model granularity through multiple levels of geometric and behavioural abstraction. We describe the integration of *qualitative* and *quantitative* knowledge to allow meaningful, high-level descriptions of model behaviour but also support a computational architecture capable of performing detailed, albeit approximate, quantitative analysis of an appropriate model sub-section.

1. Introduction

The deterioration of the stone of exposed sculptures and buildings has been observed throughout the centuries. However, the weathering damage of a building in its first 500 years is often mild in comparison to the decay in the last 50 years, particularly in the urban environment. This is due mainly to increased atmospheric pollution. By understanding the mechanisms involved in the decay process it is possible to develop tools to combat this decay.

Most research in stone decay has focused on the identification and quantification of individual decay mechanisms e.g. dissolution rates of limestone and measurement of gypsum crust formation. However it is not sufficient to consider these mechanisms in isolation. Rather, it is necessary to consider their interactions in the context of a building. Computer modelling provides the power to represent such interactions and direct further research.

In section 2 we introduce the domain of stone decay and discuss the role of abstraction and approximation in coping with its inherent complexity. In section 3 we detail a *causal network* architecture which provides a suitable framework to represent multiple levels of model abstraction. We further outline a system of *context management* which is responsible for the invocation and interaction of various abstracted sub-systems. In section 4 we discuss the use of approximate process models where the computational methods for simulation are based on quantitative and qualitative mechanisms depending on the level of model abstraction and the exactness of information.

2. Domain

The problem of developing a stone decay model is one of complexity. A monument contains many different components: stone blocks, mortar, dowels, slates and so on. The stone decay mechanisms are dependent on the physical and chemical properties of both the monument and those of the environment. Stone decay mechanisms include:

1. Chemical attack i.e. etching, erosion and dissolution of alkaline stones by acidic substances, both natural and man-made (volcanic gases, industrial emissions).
2. Mechanical disruption caused by expansive forces generated in pores, channels and cracks by the freezing of imbibed water, by the growth of crystals, or by the corrosion of embedded metals (iron) or minerals (pyrites).
3. Disfigurement due to the migration into the stone of coloured matter from the adjacent materials (rust and copper staining), alteration of the original colour or texture by selective leaching from the stone of one of its components or by etching and roughening of the polished surface.

A model for stone decay on the scale of a complete monument requires sufficient *scope* to integrate many different decay mechanisms and sufficient *depth* to support detailed analysis of such mechanisms in certain critical sections of the monument. Efforts in this area have sacrificed scope to achieve depth or vice-versa.

[Lipfert ‘88] worked on the quantification of formulae for atmospheric damage to calcerous stones. This provided a detailed model for a single decay mechanism acting on a specific stone type. Extending such a modelling approach to a building is an intractable problem. Other models, based on hydrogeological theories, have been created to simulate the migration of soluble salts internally through a group of stones [Nielsen ‘91]. This extended the scope of the model but focussed on a single decay mechanism i.e. generalisation of fluid flow through stone.

We require a model catering for many decay mechanisms on the scale of a building while retaining sufficient detail to meet the needs of the user. We suggest that such a large scale model does not imply a large scale solution. Instead, we render the intractabilities of scale and scope tractable through intelligent use of abstraction and simplification. Advances in the field of qualitative physics [Forbus ‘90], [Forbus and Falkenheimer ‘91], [Nayak et al ‘91] provide a foundation for the management of multiple levels of abstraction and approximation.

Typically, it is feasible to decompose a physical system as complex as a building into sub-systems based on high-level commonalities of behaviour e.g. groups of blocks in a wall may act similarly. Only some portions of this model may prove worthy of further investigation. Detailed analysis need only be performed on key sections of the larger model to allow the user to understand the general behaviour of the monument and the specific behaviour of critical sections. Allowing progressive refinement of model granularity is analogous to dynamic alteration to the depth and scope of the model.

In this paper we propose a model architecture which embodies this successive refinement approach through multiple levels of geometric and behavioural abstraction. Furthermore, we describe the integration of qualitative (i.e. symbolic values) and quantitative (i.e. numeric intervals) knowledge to allow meaningful, high-level descriptions of model behaviour but also support a computational architecture capable of performing detailed, albeit approximate, quantitative analysis of an appropriate model sub-section.

3. An Architecture for Multiple Granularities

A complete building, as shown in figure 1, may be represented as a network of distinct components e.g. roof tiles, bricks, mortar etc. Figure 2 shows a partial view of this network. The behaviour of the monument is derived through the local interactions of the parts represented in this network. Links join components which are physically in contact and are the pathways for such interactions. The behaviour of each component is *context dependent*. The context of a component is a local perspective of the system behaviour i.e. any direct influences on that particular component. A context is constructed by referring to the interactions between the component and its neighbours in the network.

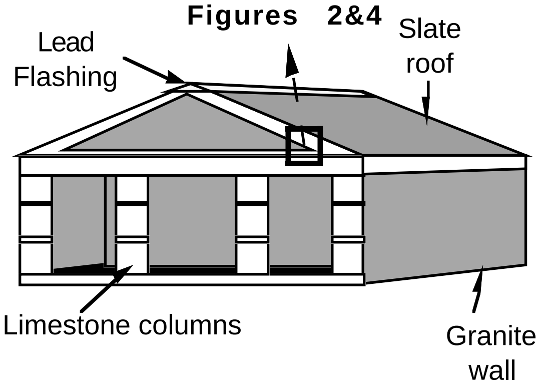


Figure 1: Maximum Scenario

In this network model, the smallest unit of decomposition is the single component (e.g. a brick) and the basis for linking components is physical contact. Locality is the fundamental organising principle. Such an architecture supports multiple levels of abstraction.

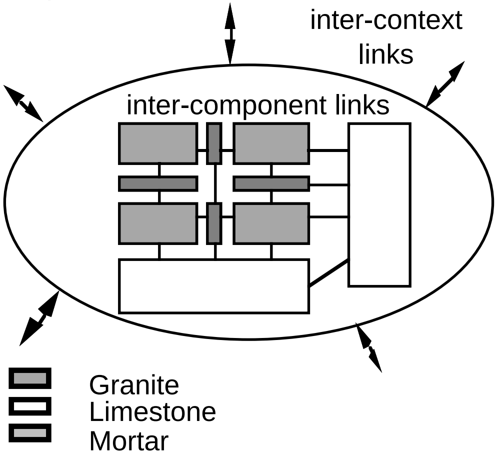


Figure 2:
Causal Network Partial View

We identify a *maximum scenario* (figure 1) and *a minimum scenario* (surface representation only, as in figure 3) reflecting the granularity of the end points of the abstraction spectrum.

Our model architecture allows many levels of abstraction within these limits. A *context manager* is responsible for aggregating contexts based on commonalities in geometry and behaviour. Inter-component links give way to inter-context links. The appropriate level of abstraction is determined by the level of user query. If the user is conducting preliminary investigations, it may be sufficient to describe the building in terms of dry, washed or unwashed regions. A query requiring a slightly more detailed response might result in the system predicting a sulphated crust formation in the sheltered area shown in figure 4. The maximum scenario representation enables investigation of behaviour within a single component.

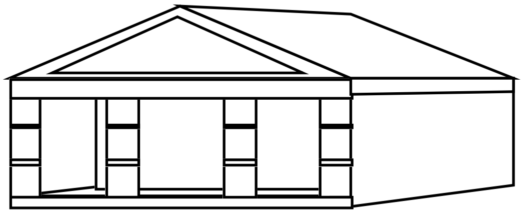
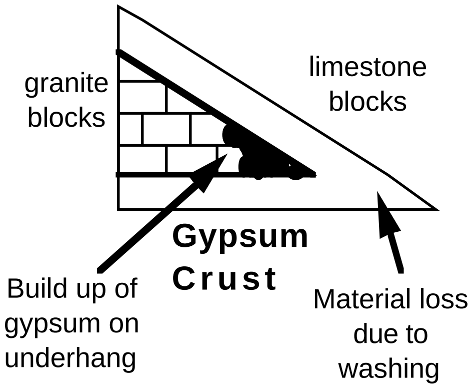


Figure 3: Minimum Scenario

4. Levels of approximation in knowledge representation

Network links contain transfer parameters representing the interactions between nodes. Process models dictate how these parameters are derived and interpreted. There may be many different models for any given process arranged according to the approximations they incur and the abstractions they require. The governing principle in selecting a process model is *sufficiency.* Consider the growth mechanism of sulphated crusts on urban limestone outlined in figure 4. This phenomena occurs in areas of the building that get wet but are not washed by rain. For a high level of model abstraction it may be sufficient to approximate this process to a prediction of the formation of gypsum crust in these wet, unwashed areas. Such predictions are based on geometric characteristics and wind/rain patterns. Where more focussed investigation is required we might incorporate the full mechanism described in figure 4 which, in addition, draws on information relating to water and salt migration, dissolution rates and deposition rates.



Sulphur dioxide is dissolved in water and penetrates the stone.

Internally it reacts with calcium carbonate to form calcium sulphate in solution.

Capillary action and evaporation mechanisms causes the calcium sulphate to be transported to the surface and crystallize forming gypsum.

The presence of this gypsum causes the decay mechansim to accelerate in that area by further acidifying any water passing over it.

**Figure 4:
Gypsum Crust Formation**

Process models are invoked and modified dynamically based on the current operating conditions in the model i.e. the context.

Allowing many different levels of approximation in knowledge representation is essential in the domain of stone decay. Often the exactness of the domain knowledge varies. The precise details of the leeching process by capillary action (mentioned in figure 4) are not known although we can give good approximations [Nielsen ‘91]. In contrast we can resort to differential equations to represent more traditional, well explored domains e.g. stress analysis. Mixing qualitative and quantitative knowledge supports such variance. A preliminary version of such a system built for more traditional engineering problems such as stress analysis [McGann ‘91] shows promising results.

5. Summary

In this paper we have looked at modelling stone decay in buildings. In particular, we suggest that multiple levels of abstraction and approximation overcome the intractabilities inherent in a physical system as structurally complex as a building where many different mechanisms interact freely. We have identified the need for sufficient scope to reason about a number of decay mechanisms and sufficient depth to provide the level of detail required by the user. In recognition that detailed information is only necessary in critical sections of a complete model, we use multiple levels of abstraction to refine our representation as the users attention becomes more focussed. A causal network architecture provides a framework to support this.

We employ many levels of approximation in knowledge representation. There are two reasons for this. Firstly, because the decay mechanisms are often based on inexact knowledge we simply do not have precise quantifications of certain processes. Secondly, we are interested in providing *sufficient* detail in analysis. The level of user queries dictates what is sufficient. Computational expediency makes it essential that the maximum approximation is employed. We use a mixture of quantitative and qualitative knowledge to facilitate this.

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