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The Role of Equilibrium Analysis in Structural Assessment

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Summary

Equilibrium analysis in its simplest form is a mechanical process of hang weights from strings to represent the mass and geometry of a structure. In this form it was used from the days of Hook and Wren, but found its greatest exponent in Gaudi. The advent of microcomputers and spreadsheets offers the opportunity to build such models much more quickly. They are, of course, virtual models but the nodes can be moved with much greater ease.

The view of flow of force, which comes from a calculated model, is more complex and more complete than that from a physical string model. A complex structure, one that does not lie in a single vertical plane, is examined in some detail to explore some of these complications.

Keywords: Gravity, masonry, arch, buttress, equilibrium, thrust-line.

1. Equilibrium Analysis

Equilibrium analysis is the study of the flow of forces. It is common to use thrust lines and similar tools to visualise the output from modern finite element analyses but sketching thrust lines with the aid of a computer is very useful, at least for initial studies. There are disadvantages in this simple view of structural action and some of them will be discussed. Usually the advantages far outweigh the disadvantages.

Specialist programmes have been written for arch bridge analysis. They cannot easily be applied to others structures. The development of the spreadsheet has made it possible, and indeed quick and easy, to develop equilibrium analyses of complex and original structures.

The representation of the forces and the division of the structure into elements must be optimised. The forces are best represented as vectors positioned by moments. The process is one of accumulation of forces.

1.1 Visualisation

Visualisation of the flow of force is a complex issue. In two dimensions, the line of thrust or zone of thrust shows clearly whether the forces can be equilibrated in the structure. In three-dimensional skeletal structures it becomes necessary to rotate the view in order to explore the alignment of forces and structure. Modifications to the picture may be required. It will be necessary to represent the outlines of the structure and the path of the forces in a way, which is easily digested by the engineer.

Presenting the results of two-dimensional calculations is relatively straightforward. In three dimensions, the problem is more difficult. If every cross section is rectangular, two orthogonal views tell the whole story but that is rarely the case. It is convenient to draw just the perimeter of the mating face between elements. In most views, this provides an understandable representation of the structure.

Interaction with the model can be achieved by typing values into cells to adjust the redundant actions. This is slow, which detracts considerably from the rate at which understanding can grow. Alternatives include pick lists, slider bars, spin buttons etc. available from Excel 97.

1.2 Wells Cathedral Skew Buttresses

The east wall of the choir at Wells is supported by two flying buttresses, which extend eastwards and drop to a relatively flat leaded roof. Below, they are supported on slender columns, which are offset from the axis of the buttress.

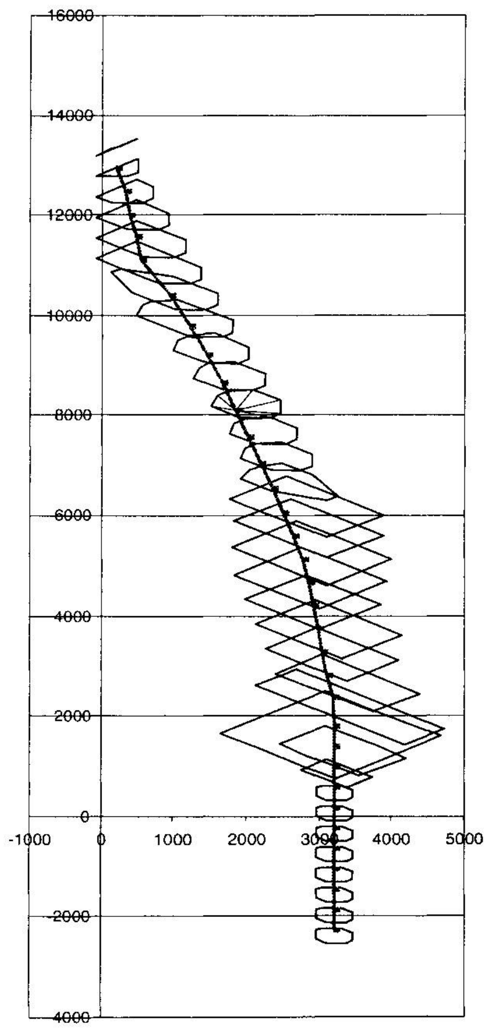

Figure 1 Buttress on Offset Pier

We have become used to ensuring that thrust lines run through appropriate points in a structure. The corresponding shear forces are usually small enough to be safely ignored. In a slender skeletal structure such as this, the shear may not act at the centroid of the section, or even at the centroid of that section which is in compression. There will thus be a twisting moment or wrench at any section. That twisting moment must be considered, even if the engineer then decides it is small enough to be ignored. The twist and shear is not easily visualised, nor is it easy to interpret.

Figure 8 shows an oblique view of a line of thrust in the buttress.

2. Discussion

A rather more complex model is quite manageable. It would entail introducing further points of interaction to deal with the additional redundancies. Structures that are not inherently skeletal are more difficult to deal with. The author is pursuing alternative forms of discretisation, interaction, calculation and visualisation. In the mean time, the models demonstrated offer a simple way of exploring potential behaviour in complex, particularly old, structures.

A number of issues are raised which leave difficult questions for the engineer. The interaction of a stiff structure with its more flexible surroundings is not well understood. Good models can highlight this but they can also help the engineer to apply judgement.

The three dimensional model of the Wells buttress is capable of dealing with further load systems, of which wind is most likely to be significant. Further work on the model will be allied to developing ideas on interaction and visualisation techniques. There is also potential for considering different models of details of the structure. One possibility is that the simple thrust line could be replaced with a three dimensional strut and tie model in critical regions.