Form finding and branching structures

Stuart Guarniere and Clare Whitworth write about their undergraduate project at Warwick University which was highly commended in the 2004 Model Analysis Award

This report presents the results of investigation into the design of branching structures that can be constructed from materials such as structural steel. The purpose of the work was to compare the efficiency of branching structures, produced using form-finding techniques, with conventional, dictated structural design.

It was the intention to produce a branching structure supporting a flat roof and compare it with conventional roof supporting structures, in terms of overall steel weight and deflections, with the aim of producing a branching structure which was more efficient than the conventional structure. Eight design criteria were generated from the study of trees which would govern any designs produced. It was decided that which satisfied all criteria and other mentioned requirements, i.e. minimum weight of steel and member deflections, would be constructed as a scaled model. This approach allowed visualisation of the physical appearance of the model and its likely performance.

Research

Initial research was split into two parts covering engineered branching forms currently in existence and the natural forms that trees take. The major design criteria were drawn from this information.

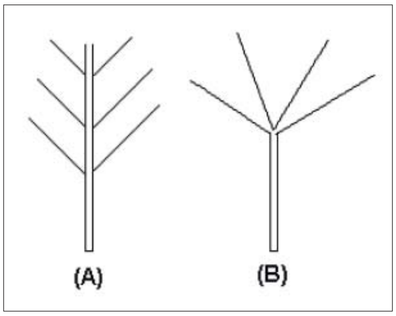
It was found from examining the trees that, if a very simplified approach is taken, there are two distinct types of tree forms. The first type (A) consisted of a central trunk to summit with branches extending at several points. The second type (B) consisted of a trunk which was not continuous up to the summit of the tree and where the main branches forming the canopy extended from this single point) (Fig 1).

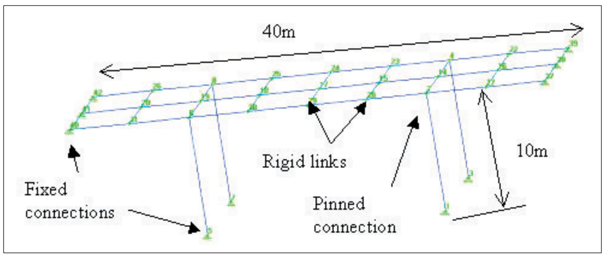
Type (B) structure was considered the most appropriate on which to base branching structure forms for analysis, as loading from all the branches would be directly transferred to the trunk. Smaller sections sizes could be chosen for the branches, leading into a larger trunk section to transfer load to the ground.

From further examination of trees, including measurement of branches and the angles of orientation of branches from the main trunk, further assumptions were made which would form basic design criteria as follows:

- Designs should be based on the type (B) tree structure as defined. One trunk separating into main branches, which in turn separate further into sub-branches.
- The number of main branches separating from the trunk should be between two and six. The sub-branches extending from the main branches should be in groups of two or three.
- The angle of orientation of the main branches should be between 30°–60° from horizontal, as this was the range of angles found when examining the branches for actual trees.
- The trunk of the branching structure designs should not be taller than the canopy of the tree. The canopy of the tree should be of similar width in all directions. This provides structural stability and resistance to external forces.

It proved useful to examine existing branching structures and forms resembling trees which have been used in architecture. Branching structures have been used as supports for roofs and canopies, in particular those of centrepiece structures, such as airport terminals.





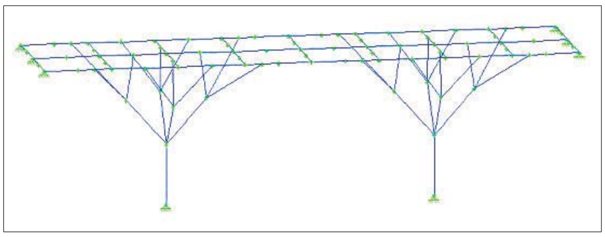


Fig 1. (right) Tree Forms
Fig 2. (below) STRAP schematic of the conventional structure
Fig 3. (bottom) STRAP schematic of the final design

From examining existing branching structures, including those at Stuttgart airport, Stansted airport and the Stranraer Academy the following design parameters were identified:

- Circular hollow steel sections should be used as these best represent the circular branches and trunks of trees. Circular hollow sections are effective at transferring load in tension and compression, and are often used for light-weight truss structures, which make use of triangular shapes similar to the existing tree structures.
- Examination of existing structures suggested that the branches of the tree structures should make use of sub-branches in groups of three, which are to be attached to the roof structure. This would allow stable pyramid shapes to be created together with the best transfer of load from the roof.
- Some of the existing structures examined used leaning trunks or supported sloping roofs, which produced a natural appearance. In order to keep the computational modelling simple this was not to be applied to the initial designs. Therefore, care should be taken to ensure a natural appearance is achieved.
- The sections sizes of the trunk, branches and sub-branches should decrease in size to provide a more realistic appearance and to optimise load transfer from the roof to the trunk of the tree structures.

Design

In order to allow for comparison of branching structure designs with conventional construction a conventional roof structure design was produced. This was analysed using STRAP (Structural Analysis Software) and is shown in Fig 2.

The primary and secondary members of the roof were rigidly linked together to provide the load distribution comparable to that of a one-way spanning roof slab. The beam sections were determined from hand calculations and the column sections were determined by adding the 2kN uniformly distributed load to the roof members and systematically reducing their section size until they were operating in the most efficient manner, i.e. the section size at which the majority of its axial load capacity was needed. The roof deflections were then checked using span/200, as stipulated by BS 5950.

The production of the conventional roof structure allowed comparison with the branching structure designs, which were then developed. The branching structure designs produced were based on the eight design criteria defined earlier. The creation of the branching structures was very much an iterative process, based on initial sketches, then analysed using structural software and modified to increase structural efficiency. The final branching structure design can be seen in Fig 3.

The final design was constructed using aluminium rod and Perspex glass, to allow the structure to be visualised more clearly than was possible from the STRAP schematics. The rods were then wrapped in copper wire to help enunciate the differences in section sizes as seen in Fig 4.

Analysis

The following tables compare the structural efficiency of the final design and the conventional roof model.

The large percentage use of the allowable stress of the members shows the efficiency of the design, due to the short load path and the minimisation of section sizes, as can be seen in Table 1. The section sizes could have been further reduced although this was not applied, as it would deter from the tree-like appearance of the forms.

The deflections of the roof beams, as seen in Table 2, are significantly lower for the branching structure. This is due to the reduced unsupported span. If a roof structure is to be constructed of a brittle material, such as glass, branching structure supports would be an ideal choice, as the minimal deflections suggest that this would be possible without cracking, or large horizontal beam supports.

Table 3 shows the nominal weight saving between the designs. This seems more significant when it is realised that there are 17 components of the tree structure, compared with only 2 columns in the conventional design. The use of many small sections also allows for easier transport and handling compared with two, 10m-long columns. However, the construction of the design would be significantly more complicated due to difficulties of joining tubes at different angles.

An advantage of using this branching structure, compared to the two column design is that there is only one support at ground level, compared with two for the columns. The use of one main central support is often applied to tower blocks, to allow better use of the floor space. However, the structures cannot be used where unobstructed height is needed, as the branches extend in all directions from a height of 4m in the case of the final design. This is one of the reasons why branching structures are used for showpiece architecture, where space is needed at ground level but unobstructed height is not necessary.

A disadvantage of the structure is the lengthy design process involved compared to column design procedures, especially considering the standard codes of practice available for conventional roofs and columns which do not consider branching structures. This is because the forms are 'found' and not designed on the basis of a contrived shape.

As the structure has been designed for a particular purpose, i.e. to support a roof, there is an element of dictation in the design which would otherwise not be there. This is because trees do not support only the type of external loading assumed in this case. Therefore, this type of function was engineered into the design. Thus the design process deviated slightly from the true form-finding procedure, as used in tension structure design.

Table 1: Axial stress values

Members	Allowable axial stress (max)
Trunk	61%
Main branches	61%
Sub branches	99%
Conventional Columns	81%

Table 2: Deflection values

Structure	Deflection (maximum) m
Tree structure – final design	0.0033
Conventional column structure	0.043
Percentage deflection reduction = 92.3%	

Table 3: Weight values

Structure	Weight kg
Tree structure x 2 – final design	1833
Conventional column x 4 structure	1844
Percent weight saving = 0.65%	

It is important to note that the structure was analysed under the assumption that it was perfectly pinned, allowing no moment resistance in the joints. All loads were assumed to be transmitted axially through the structure, and a nominal horizontal load of 2.5% of the total vertical load was applied to conform to recommendations in BS 5950 with regard to lateral stability.

In spite of the deviation from true form-finding process, (as applicable to tension structures, for example), and the disadvantages mentioned above, the proposed branching structure design is aesthetically superior to conventional construction. Furthermore, branching structures provide a focal point to a piece of architecture rather than just fulfilling the function of columns. This is reinforced by the structural advantages, such as allowing the use of lightweight roof structures, unobstructed floor space and an efficient use of materials.

This investigation has shown that the process of form-finding can be used to achieve designs, which promise to be both structurally efficient and aesthetically pleasing, without the necessity for complete dictation of form at the outset.

The finalised branching design, within the adopted idealisations, appears structurally more efficient than the conventional column design. The tree structure contains a lower steel weight, because the sections chosen use a significant proportion of their axial load capacity and the angles of the branches providing short load paths. The deflections of the roof structure are significantly smaller than those in the conventional column structure. The modelled branching structure is also aesthetically superior to the conventional design.

Apart from the reduction in weight, the advantage of the design is the reduction of unsupported spans for the roof structure, due to the arrangement of branches, which reduces the deflections of the roof beams. It is likely that smaller roof beams could be employed than currently used in comparable conventional designs due to reduced influence from bending. As branching structures make use of more components than conventional design for the same weight the sections are lightweight which enables easier handling and transport.

The disadvantages of the branching structure design include the lengthy design process involved compared to standard column design procedures. As the structure is designed for a particular purpose, i.e. to support a roof, there is an element of dictation in the design which would otherwise not be there. This causes the design procedure to deviate from the form-finding process used in, for example, advanced tension structures.

Finally, construction of the branching design would be significantly longer and more complicated due to the number of sections required. This also applies to connections. It is clear that this would significantly increase the cost in terms of both design and construction when compared to conventional structural steel forms. This is why branching structures are only used for showpiece architecture, as has been seen in existing engineering constructions.

One additional limitation in the analysis of the branching structure should be noted. The structure was assumed to be perfectly pinned so that pure axial loading could be considered. In reality, the connections would be able to resist some moment, and this feature should be addressed by a more comprehensive analysis.

The aesthetic appeal and, based on this limited study, the efficiency of branching structures, are overwhelmingly superior, when compared to conventional column design. The disadvantages should not detract from this observation. In this urban age, it is important to consider the visual impact of construction on the environment. Designs based on nature provide a welcome diversion from the culture of designing for low, short-term cost, rather than for long term cost efficiency. se

Fig 4. Model of the final branching structure design