Experimental study on structural behaviour of branching steel columns

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Abstract. Few researchers have study the branching column and there is no enough information about it. The objects of this research is to study the structural behaviour of the branching columns and how it effects on the form-finding. These branching columns are experimentally tested and preparation tables to assist with design of it. Experimental work was carried out on the seventeen specimens. All specimens have been tested under static load then evaluated for maximum failure load, maximum vertical displacement and failure mode. The studied variables are the ratio of horizontal spacing between branches to total width of specimen, number of branches and number of branching level. The results showed that when the ratio between the width of the specimen and the overall width was increased, failure load and buckling load was decreased and maximum vertical displacement was increased. When the number of branches increases, the failure load increases slightly, with the vertical displacement increasing. The failure load, buckling load decreased and the vertical displacement greatly increased as the number of branching levels increases. All specimens have failed with buckling mode, and had less failure load and buckling load than the reference specimen.

1. Introduction

Trees are a great source, which were inspired many architects and construction engineering because of their uniform design and strong structure which is capable of resisting the hugest load like wind [1]. One of the benefits of using branch columns which cover a large surface area with near bearing points. The other benefit of the dendrite is a wide area of the floors that is tolerable and architecturally distinguished. There are few studies on the topic. Frei Otto [2] was one of the first engineers to take an interest in the lightweight branching systems. He discussed the hanging structures, domes and branch columns, in particular. Kolodziejczyk [3] was used to carry out the form-finding study using thread specimens put in water. The minimum path of pseudo force was derived using water surface tension. Wu [4] proposed the reverse hang recursive method for branching structure form optimization. The experimental approach was primarily used in earlier form-finding studies. However, this method is time-consuming, tedious and could not be used for complex projects. Numerical methods have become the primary method of study for technical issues of computational technology development and attracted many researchers’ attention. In order to conduct form finding analysis, Buelow [3] used the genetic algorithm (GA). Hunt [5] proposed to use a numerical method where tree structures are supposed to be connected to hinge and pseudo supports are added to maintain a positive stiffness matrix in a vertical direction. Zhang [6] simulated the cable element tensioning-only features to decrease the moment of bending of the structures of the tree. Ahmeti [7] analysis a group of branching column by using BUILD SIMULATION SOFTWARE and compared between them in order to learn about each column type's
structural behaviour. Kai-Ume Bletzinger [3] has been using the CARAT program to evaluate axial loads of specimens. These studies have demonstrated the importance of form-finding analysis in tree structure research and design. No single method can efficiently solve the problems in the development of branching structures of topological nature, shape analysis and mechanical optimization. Branches are located in a number of buildings around the world, including at Stuttgart Airport in Germany, Berlin's Olympic Stadium, Riyadh King Fahd Building, Saudi Arabia and the Melon Justice Palace in France. As figure (1) shows Several buildings of this kind.

2. Objectives
The objective of this research is to find the structural behaviour of branching steel column experimentally. Seventeen specimen s were tested with different ratio between the width of specimen and overall width, different number of branches in final level and different number of branching levels. The failure load, buckling load, vertical displacement, and mode of failure were presented in tables to simplify the design of branching steel column structure.

![Figure 1](image1.jpg)

**Figure 1.** Building has branching steel column [1].

3. Classification of branching column
There is no consistent and standard method for classifying branching columns. Previous studies did not classify this type clearly and uniformly. To classify this topic, some terms used to classify trees were used. The classification of the branching columns was done based on the amount of branching levels and number of branches in the final level of branching. For example, the branching column that is shown in figure (2) have a name (4BL-16B) where 4BL refer to four branching levels and 16B refer to sixteen branches. It is possible to add other symbols for the purpose of showing some details such as symmetry or asymmetry and the ratio of tree width to total available width, etc. The branching structure components can be categorized according to their position with respect to the trunk. Branches that sprout from the trunk are known as branches of the first level, and the branches of the components belonging to branches of the first level are categorized as branches of the second level. Components branches belonging to branches at its level are classified as branches at (i+1) level. A trunk and two branches are the simplest branching column type.

4. Geometric parameters of branching column specimen

4.1. Cross section area of trunk \((A_0)\)
From the above studies that dealt with the subject, there is no clear relationship between the load and the cross section area of the branching column trunk. Many data on this topic were gathered from researches on the relationship between height and tree trunk area, as well as information from projects implemented around the world. The data collected represent the trunk area, height, type of tree, as well as the material from which it was created. It is clearly that the urgent need to analyse these data into common elements that can be used in the research and to reach a satisfactory and convincing result. The amount of axial hardness (see Eq.1) was chosen to be an element that connects all types of trees and the implemented projects around the world. Table (1) shows the axial hardness of a group of trees with the axial stiffness of a group of construction projects. From the table below, it found that the maximum amount of tree axial stiffness is 300 GPa, while for the projects established in the world between 300 to 500 GPa. In this research was selected axial hardness by 300 GPa because this amount is the boundary between trees and projects implemented in the world and this amount was fixed for all specimens during research. When the axial stiffness amount was fixed at 300 GPa and the use of modules of elasticity (E) equal to 200000 MPa, a relationship was found between the total height of the branching steel column with its sectional area. A rectangular section was selected for all specimen s in the research and the cross section area of trunk equal to 480 Mm2.

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(K = \frac{EA}{L})
\]

Figure 2. Branching levels of branching column [8].

4.2. Sequence of cross section area
The cross-sectional component areas in each level were referred to as A1, A2, A3, A4, ..., An, where n is the highest branch structure respectively. There are many sequences of area used by researchers [8 and 9]. The sequence that was used in this research is that the suffix area equals the area of the preceding and divided by the number of branches.

4.3. Ratio between the width of specimen and overall width (W/WT)
The inspection ratio between the total height to the total width was taken about 1:1, where it represents the total plane area available for the construction of the branching column on it. The horizontal spacing of the specimens was varied from 87.5 mm to 350 mm in this research.

4.4. Number of branching level (BL)
In this research, two levels of branching were taken with the non-branching specimen (ordinary column), which were considered as reference specimen. The first and second levels of the branch were studied, because these two levels are practical and implementations in some projects.
4. Number of branches (BN)

The number of branches in the specimens with first branching level was changed, as two, three and four branches in addition to the reference specimen which were considered to be a single branch specimen.

Table 1. Axial stiffness of many types of structures.

| Branching Structure Name | Axial Stiffness (GPa) | Type of Structure | Branching Structure Name | Axial Stiffness (GPa) | Type of Structure |
|--------------------------|-----------------------|-------------------|--------------------------|-----------------------|-------------------|
| Eucalyptus               | 11.7                  | Natural           | Tectona grandis          | 187.4                 | Natural structure |
| Betula pendula           | 12.2                  | Natural           | Vitellaria paradoxa      | 302.0                 | Natural structure |
| White spruce             | 16.8                  | Natural           | Stuttgart airport (line | 305.2                 | Industrial        |
| Loblolly pine            | 26.2                  | Natural           | BCE culture square       | 312.4                 | Industrial        |
| Acacia savanna           | 34.8                  | Natural           | Beaverton library        | 349.2                 | Industrial        |
| Cunninghamii             | 44.3                  | Natural           | New Changsha             | 357.9                 | Industrial        |
| Araucaria                | 49.0                  | Natural           | Stuttgart airport (line | 389.3                 | Industrial        |
| Flindersia               | 63.2                  | Natural           | Stuttgart airport (line | 442.9                 | Industrial        |
| Picea sitchensis         | 97.6                  | Natural           | University of Guelph     | 572.6                 | Industrial        |

5. Experimental investigation

5.1. Description of branching column specimens

Seventeen branching column specimens used in this research program. Each column cover area that has a total height (HT) equal to 350 mm and total width (WT) equal to 350 mm. Specimens are divided into five groups, where each group consisting of only four specimens except group one consists from reference specimen. The first group specimens have trunk only without any branch. The second group specimens have trunk with two branches only in the first branching level. The third group specimens have trunk with three branches only in the first branching level. The fourth group specimens have a trunk with four branches only in the first branching level. The fifth group specimens have trunk with two branches in the first branching level and four branches in second branching levels. All specimens have a rectangular cross-section (A0 = 480 Mm²) in the trunk. When specimens have first branched level, each branch has a cross section area equal to half area of a cross section area of trunk (A1 = A0 / 2). Also when, the specimens have second branching level, each branch has a cross section area equal to quarter area of a cross section area of trunk (A2 = A0 / 4) or (A2 = A1 / 2).

5.2. Manufacturing of Specimens

All specimens were made from 12 mm steel plate that passing in chemical and physical testing and compliant with the specifications of ASTM A 605 [10] (see Table (2) and Table (3). Steel plate tensile testing was performed using the method described in ASTM A370 [11] and ASTM A36 [12], and chemical testing was performed using the method described in BS 4449 [13]. The plate cut by using computer numerical control (CNC) machine. Specimens are provided with steel bases that are fixed to the specimen by using welding compliance with AWS A5.1 E6013 [14]. Destructive welding tests NDT have been conducted to ensure the highest standard of welding specimens and are suitable for concept fixation. To ensure its consistency, Visual test VT [15] and penetrating test PT [16] were carried out on welding. The steel bases containing holes for fixed the specimen to the testing machine by 17 mm diameter steel screws. The welding method was electric arc covered electrode J38.12 / E6013 [14]. During the manufacture of the specimen, the horizontal and vertical straightness of all were checked. All specimens were dyed by spraying device.
5.3. Loading procedure

A static load was carried out with the use of a hydraulic tester as shown in figure (3) and has an output of 400 kN. The unit also has an LCD screen for correct reading of the results and all the sensors needed, and is calibrated by Iraq's Central Organization for Standardization and Quality Control (COSQC) [17].

The specimens were linked to the frame using 17 mm screws, two at the base and two or four at the top, in order to achieve the fixed support on top and bottom of the specimens. Then load was applied uniformly to the top of the specimens with rate 0.2 kN / sec. The Linear Variable Differential Transformer -LVDT sensor was used on top of the specimens to evaluate the vertical displacement. For reading load, vertical displacement, and specimens strain, DATD LOGGER were used. Steel strain gage style FLAB- 5-11-3- LJC-F [18] was used with a length of 5 mm and 120 ohms to calculate the vertical strain at the branching area. The result has been extracted and transferred to excel to see the overall failure load for each specimen along with the corresponding vertical displacement and load-strain curve for each specimen.

| Test name               | Specimen | ASTM A36/A36 M limits (min.) |
|------------------------|----------|-----------------------------|
| Yield point, min, (MPa)| 426      | 250                         |
| Tensile strength, min, (MPa) | 666      | 550                         |
| Elongation, min, (%)    | 22       | 20                          |

| Test name       | Specimen | ASTM A36/A36 M limits (min.) |
|-----------------|----------|-----------------------------|
| Carbon, max, %  | 0.210    | 0.25                        |
| Manganese, %    | ---      | ---                         |
| Phosphorus, max, % | 0.040  | 0.04                        |
| Sulfur, max, %  | 0.034    | 0.05                        |
| Silicon, max, % | 0.371    | 0.40                        |
| Copper, min, %  | 0.410    | 0.20                        |

Figure 3. Branching column specimen setup.
6. Results and discussion

6.1. Load-displacement response
The specimens were divided into five groups, each group consisting of four specimens with the exception of group one consisting of one specimen. All specimens were labelled with four codes except for the reference specimen labelled T-R. For instance, in the B-1BL-2B-25 symbol, where the first code refers to a branching column, the second code refers to the number of branching levels, the third code refers to the number of branches, and the fourth code refers to ratio between the width of specimen and overall width. Load – vertical displacement curve will be shown in figure (4) for all evaluated branching column specimens. When look to the specimen load-displacement response, it consists of three stages. The first stage is a linear relation between the load and the vertical movement because each increase of the load applied is balanced by an increase of the movement. This stage showed a large slope of the load-displacement curve. The second stage, which was shorter than the first stage, increased load and decreased the load-displacement curve slope. The load displacement curve tends to be non — linear when the load reaches the highest failure value (in stage three); a signal for the branching column entering an elastic-plastic state. The plastic zone of the specimens is rapidly expanded by changing the slope of the load displacement curve since a small charge increase leads to a great increase in displacement. When the ratio between the width of specimen and overall width (W/WT) increases, the slope of curve becoming smaller in all the stages.

6.2. Load-strain response
For all specimens, the strain value at the branching area has been measured to predict what will happen here. The point of the first buckle phase was also established by the load-strain curve, figure (5) shown the load-strain response for specimens. It found the buckling load was decreased when the (W/WT) was increased.

6.3. Failure load and failure displacement
Table (4) below shows the results of effect of ratio between the width of specimen and overall width (W/WT), effect the number of branches and effect increased the branching levels on the maximum failure load, buckling load of the specimens. The maximum failure load was reduced when the ratio of the specimen width and overall width (W/WT) increases for two branches in first branching level case. The same result in three and four branches cases. Also in case of second branching level the failure load was decreased when (W/WT) was increased. The decreasing in the failure load because the critical buckling length of the branches became shorter when this percent was increase and the trunk length remained constant. The maximum vertical displacement increased when the ratio of the specimen width and overall width (W/WT) increases in all cases of branching level and branch number. However, it is noted that the increase in vertical displacement has become very large in the specimen when testing specimen with two levels of branching. The increase in the vertical displacement is due to the increase in the lengths of the branches, because the shape of the specimen which increases the elasticity of the specimens, as the branches of trees work to resist storms. When the number of branches increased the failure load was increased, but the vertical displacement was decreased. When the number of branching levels was increased the failure load was decreased and the vertical displacement was increased. The vertical displacement of all specimens is greater than the vertical displacement of the reference specimen.

6.4. Specimens efficiency and specimens failure mode
The percentage of efficiency has been determined using each specimen's failure load to the reference load. Where it is found that the efficiency was decreased when (W/WT) and number of branching levels increased. Also, the efficiency was increased when the number of branches increased. This increase is due to the increased stiffness of the specimens, where the maximum load increases and the vertical
displacement decreases. All specimens have efficiency less than 100%. The specimen’s efficiency percent shown in Table (4). Failure mode was generally buckling for all specimens as shown in figure (6).

**Table 4. Maximum failure load, buckling load and vertical displacement of specimens.**

| Specimen Code | Group | Failure Load (kN) | Buckling Load (kN) | Vertical Displacement (mm) | Efficiency (%) |
|---------------|-------|-------------------|--------------------|-----------------------------|----------------|
| T-R           | Group 1 | 89.0              | 65.5               | 0.800                       | 100            |
| B-1BL-2B-25   |       | 81.0              | 65.0               | 0.916                       | 91.0           |
| B-1BL-2B-50   |       | 75.0              | 58.0               | 0.962                       | 84.3           |
| B-1BL-2B-75   |       | 69.0              | 52.0               | 1.047                       | 77.5           |
| B-1BL-2B-25   |       | 53.0              | 37.0               | 1.213                       | 59.6           |
| B-1BL-3B-25   | Group 2 | 84.0              | 66.0               | 0.827                       | 94.4           |
| B-1BL-3B-50   |       | 76.0              | 57.0               | 0.887                       | 85.4           |
| B-1BL-3B-75   |       | 75.0              | 54.0               | 0.906                       | 84.3           |
| B-1BL-3B-25   |       | 67.0              | 47.0               | 0.958                       | 75.3           |
| B-1BL-4B-25   | Group 3 | 85.0              | 67.0               | 0.813                       | 95.5           |
| B-1BL-4B-50   |       | 79.0              | 58.0               | 0.841                       | 88.8           |
| B-1BL-4B-75   |       | 78.0              | 55.0               | 0.889                       | 87.6           |
| B-1BL-4B-25   |       | 72.0              | 48.0               | 0.950                       | 80.9           |
| B-2BL-4B-25   | Group 4 | 82.0              | 62.0               | 1.245                       | 92.1           |
| B-2BL-4B-50   |       | 76.0              | 57.0               | 1.604                       | 85.4           |
| B-2BL-4B-75   |       | 72.0              | 50.0               | 1.885                       | 80.9           |
| B-2BL-4B-25   |       | 59.0              | 48.0               | 1.980                       | 66.3           |
Figure 4. Load–vertical displacement curve of branching column: (a) Group 1, (b) Group 2, (c) Group 3, (d) Group 4, (e) Reference specimen.
**Figure 5.** Load–strain response of branching column: (a) Group 1, (b) Group 2, (c) Group 3, (d) Group 4, (e) Reference specimen.
7. Conclusion
This study examined the branching column structure experimentally to determine its effect on the structural behaviour by altering the external appearance of the specimen. The results can be resumed as follows:

1- In all cases, the failure load and buckling load was decreased, also vertical displacement was increased when ratio of specimen width and overall width increased.
2- The stiffness of specimen decreases when the width of the sample and the overall width ratio was increased but the flexibility was increased.
3- When the number of branches increased the failure load increased and vertical displacement was decreased.
4- When the number of branching layers was increased the failure load was decreased and the vertical displacement was increased largely.
5- All specimens were failed by buckling mode.

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