Experimental Investigation of Dendriform Structure Under Static Loading

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Tree-like steel columns have been used in vast structures with large spaces like airports and football stadiums. Very few studies dealt with the structural behavior of tree-like columns, and there are non-clear results about it. The objective of this study was to find the effect of the branch's height to total height and specimen's width to total width ratio on the structural behavior of a tree-like steel column (two-branch type). Seventeen plane specimens with a rectangular cross-section area were investigated. All specimens were tested under static load and evaluated in terms of maximum failure load, maximum vertical displacement, and failure mode. The two-branches type was taken, and the cross-section area of each branch was taken half of the trunk's cross-section area. Results showed that maximum failure load and buckling load increased between (2.5 - 28.9) % and (1.4 - 37.5) % respectively when the branch's height to total height ratio increased from 25 to 75 %; furthermore, they decreased between (7.2 - 42.3) % and (8.4 - 48.4) % respectively when the specimen's width to the total width increased from 25 to 100 %. Maximum vertical displacement decreased between (5.9 - 31.3) % when branching height to total height ratio increased; moreover, it increased between (2.0 - 46.2) % when the specimen width to total width increased. All specimens failed with buckling mode.

Keywords: Tree-like column, branching structure, lightweight, Dendriform structures.

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1. Introduction

Many designers have preferred forms that combine in the wilderness, and it has a strong structure like trees and forests. One of the benefits of using tree-like columns is that they cover a large surface area with near bearing points. There are three methods for the form-finding of tree-like columns: the experimental methods, the geometric methods, and the numerical methods. Experimental methods have a technique of wet thread, dry thread, beaded thread, etc. Its results influenced by the scale of the model. Frei Otto [1] was one of the first engineers to take an interest in the lightweight tree-like systems with the experimental method. Kolodziejczyk [2] used the waterish logging thread model to carry out the form-finding of branching structures. Geometrical methods introduce fractal theory to produce tree-like geometric shapes. Gawell produced geometric tree-like forms based on L-system fractal theory and applicate it in Tote Restaurant in Mumbai [3]. The tree-like shapes produced by the fractal method only focus on the forms of trees. By using the structure optimizing technology, they can improve their geometrical configuration to take into account the mechanical features of the trees [4]. Buelow [2] used the genetic algorithm (GA) to study the tree-like structure. 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. Numerical methods used to generate tree-like forms, and use of this aspect became hotspot [6]. Zhang studied the form-finding of tree-like based on the sliding cable element [7]. Using the optimization method of skeleton structures, Changyu introduced the form-finding method of tree-like based sensitivity [8]. Meanwhile improved the evolutionary method of structural optimization (ESO) to generate the optimal topology of tree-like as a topological optimization method of continuum structures [9]. For designing the Qatar Convention Center, the enhanced ESO method was applied by Sasaki [10]. Wu [11] proposed the reverse hang recursive method for branching structure form optimization. Ahmeti [12] researched a group of branching column structures and compared them to learn about each column type's structural behavior. The new method for the strengthening (bracing) of seismically loaded steel building using branch columns that look similar to trees, used by R. Black and A. Astaneh [13]. No single method can efficiently solve the problems in the development of tree-like structures of topological nature, shape analysis, and mechanical optimization. Branch buildings appear in many buildings around the world, such as at Stuttgart Airport in Germany, the Olympic Stadium in Berlin, King Fahd Hall in Riyadh, Saudi Arabia, the Palace of Justice in Melon, France, and the Qatar International Center in Doha. As shown in Fig. 1 some of these buildings. The study's objective was to find the effect of the branch's height to total height and specimen's width to total width ratio on the structural behavior of a tree-like steel column (two-branch type) under static load experimentally in term of maximum failure load, buckling load, maximum vertical displacement, and mode of failure. Different ratios of the branch's height to total height and specimen's width to total width were tested.

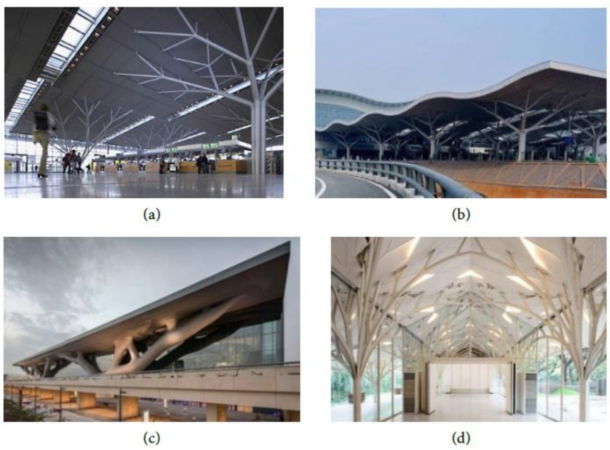

Fig. 1. Buildings with the tree-like column. (a) Stuttgart Airport Terminal, Stuttgart, Germany; (b) Changsha railway station in China; (c) Qatar national convention center; (d)Tote restaurant, Bombay [6].

2. Experimental work and Testing Procedure

2.1. Tree-Like Specimens Description

Seventeen plane specimens were used in this investigation program, where each one cover area with total height (HT) equal to 350 mm and total width (WT) equal to 350 mm. All specimens have a trunk with a rectangular cross-section area equal to 480 mm^2, and two branches each one with a cross-section area equal half of the trunk's cross-section area, as shown in Fig. 2. The specimen's width to total width ratio (W/WT) and the branch's height to total height ratio (HB/HT) were varied from (25 % to 100 %). The reference specimen was made without branch and had the only trunk with a rectangular cross-section area. Table 1 showed the dimension of the tested specimens. All specimens were made from steel, which confirms with ASTM A 605 [14], and they constructed from a 12 mm steel plate. Furthermore, they were cut using the CNC machine. Steel bases containing 17 mm diameter holes were constructed and fixed by welding in all specimens to link the specimen to the testing device by screws. The welding was done by using the electric arc method with covered electrode J38.12 / E6013. When finalizing the specimens, the vertical and horizontal equatorial was verified by leveling scale. All specimens were painted by spraying device. The specimens were divided into four groups; each group consists of four specimens. All specimens were given a label with three codes, except the reference specimen was given label TR. For example, in the label T-25-25, where the first code refers to the tree-like column, the second code refer to the branch's height to total height ratio, and the third code refers to the specimen's width to total width ratio.

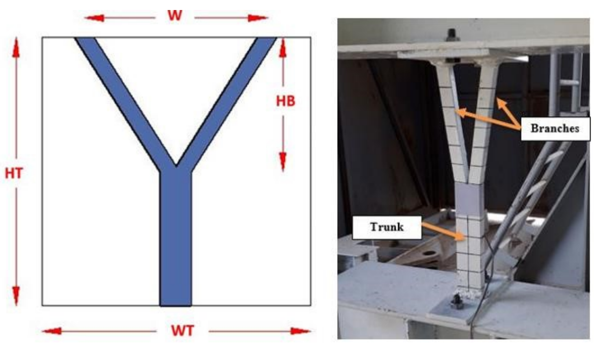

Fig. 2. Tree-like Column Specimen Details and Parameters.

2.2. Materials

The steel plate used in this study conforms to ASTM A 605 specifications [14] for the physical and chemical properties, and they are summarized in Table 2 and Table 3. The tensile test of steel plate was carried out using the method described in ASTM A370 [15], ASTM A36 [16], and chemical tests were carried out using the method described in BS 4449 [17]. As for welding, the J38.12 / E6013 welding electrode was used, matching to AWS A5.1 E6013. Also, the

Table 1. Specimens Dimensions.

Group	Specimen Code	HB (mm)	W (mm)	Trunk length (mm)
Reference	TR	Non	Non	350
Group 1	T-25-25	87.5	87.5	262.5
	T-50-25	175	87.5	175
	T-75-25	262.5	87.5	87.5
	T-100-25	350	87.5	Non
Group 2	T-25-50	87.5	175	262.5
	T-50-50	175	175	175
	T-75-50	262.5	175	87.5
	T-100-50	350	175	Non
Group 3	T-25-75	87.5	262.5	262.5
	T-50-75	175	262.5	175
	T-75-75	262.5	262.5	87.5
	T-100-75	350	262.5	Non
Group 4	T-25-100	87.5	350	262.5
	T-50-100	175	350	175
	T-75-100	262.5	350	87.5
	T-100-100	350	350	Non

welding was carried out according to the AWS structural welding specifications. Destructive welding test NDT was carried out to ensure the quality of welding and its ideality for specimen fixed. Visual test VT [18] and penetrant test PT [19] were conducted on welding to ensure its quality.

2.3. Testing Procedure

A static load test was proceeded by using a hydraulic testing machine in structure laboratory- College of Engineering- the University of Babylon, as shown in Fig. 3. It has a capacity of 400 kN and is consistent from an iron frame to support and install the specimen well. The device also has an LCD screen to read the results correctly and all the sensors needed, furthermore, it was calibrated by the Central Organization for Standardization and Quality Control (COSQC) of Iraq. The specimens were fixed to the device by using 17 mm screws, number 2 at the base and 2 or 4 at the top, to achieve the fixed support on top and bottom of specimens then the load was applied uniformly on the top of specimens with rate 0.2 kN/sec. Linear Variable Differential Transformer (LVDT) sensor was used to measure the vertical displacement on top of specimens. Steel strain gauge type FLAB- 5-11-3- LJC-F with length 5 mm and 120 ohms was used to measure the vertical strain in the branching joint. DATA LOGGER was used to read load, vertical displacement, and strain on a computer screen. The results were extracted and transferred to the Excel program to draw a load-vertical displacement curve and load-strain curve for each specimen.

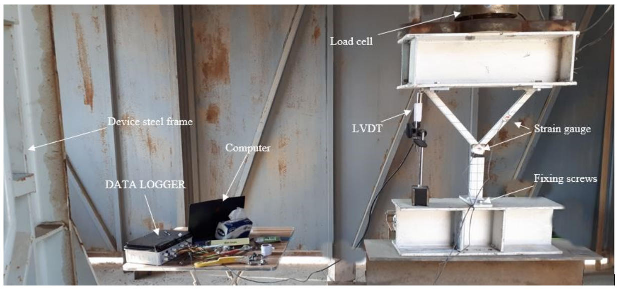

Fig. 3. Tree-like Steel Column Specimen Setup.

3. Results and discussion

3.1. Load- Displacement Response

Load – vertical displacement curve for all tested specimens are shown in Fig. 4. It consists of three parts. The first part is a linear relationship between load and vertical displacement, as an increase in displacement offsets each increase in the applied load. The second part is yielding, where it is shorter than the first part. The third part is strain hardening until specimen failure. When the ratio of the branch's height to the total height increases, the load- vertical displacement curve became steeper in the linear part, and yielding became longer. Furthermore, when the ratio of the specimen's width to total width increased, the curve became flattered in the linear part. As for the yielding, it became shorter, and the third part became longer.

Table 2. Physical Results of Steel Test.

Test name	Plat 12 Mm thickness	ASTM A36/A36 M limits (Min.)
Yield point, min, (Mpa)	426	250
Tensile strength, min, (Mpa)	666	550 for (12 Mm)
Elongation, min, (%)	22	20

Table 3. Chemical Results of Steel Test.

Test name	Plat 12 Mm thickness	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

Table 4. Failure Load, Buckling Load, and Vertical Displacement of Specimens.

Group	Specimen Code	Failure Load	Buckling load	Vertical Displacement (mm)	Efficiency
Reference	TR	89.0	65.5	0.800	100
Group 1	T-25-25	78.0	57.0	0.973	88
	T-50-25	81.0	59.0	0.916	91
	T-75-25	83.0	63.5	0.875	93
	T-100-25	80.0	61.0	0.864	90
Group 2	T-25-50	66.0	44.0	1.109	74
	T-50-50	75.0	54.0	0.962	84
	T-75-50	77.0	56.0	0.907	87
	T-100-50	71.0	53.0	0.881	80
Group 3	T-25-75	56.0	43.0	1.260	63
	T-50-75	69.0	49.0	1.047	78
	T-75-75	73.0	50.0	0.967	82
	T-100-75	60.0	42.0	0.900	67
Group 4	T-25-100	45.0	36.0	1.423	51
	T-50-100	53.0	36.5	1.215	60
	T-75-100	58.0	37.5	1.100	65
	T-100-100	49.0	31.5	0.992	55

3.2. Load- Strain Response

For all specimens, the amount of strain in the branching joint was measured. The load-strain curves in the branching joint are drawn for several reasons. The first is to know the behavior of this joint under the influence of loads, where, in some cases, it is the key to failure. The second is to know the beginning of the buckling process of specimens. For all groups, it was found that the maximum elastic stress in the branching joint increases with increasing the branch's height to total height ratio. Also, it decreases when increasing the specimen's width to the overall width ratio, as shown in Fig.5. The buckling load increases when the ratio of the branch's height to total height increases, but it decreases when the ratio of the specimen's width to total width increased.

3.3. Failure Load, Failure Displacement, and Specimens' Efficiency

Table 4 below shows the effect of the branch's height to total height (HB/HT) and specimen's width to total width (W/WT) ratios on the failure load and failure displacement. The results showed that the failure load increased between (2.5 - 28.9) % by increasing the branch's height to total height ratio from 25 to 75 % until this ratio reaches (100 %), then the increase in failure load decreased as shown in Fig 6. This increase in failure load maybe because the trunk's length became short, and the critical section of branches became large. When the ratio of the branch's height to total height is constant, the failure load decreased between (7.2 - 42.3) % with increasing the ratio of the specimen's width to the total width from 25 to 100 %. When the ratio of the branch's height to total height increased, the amount

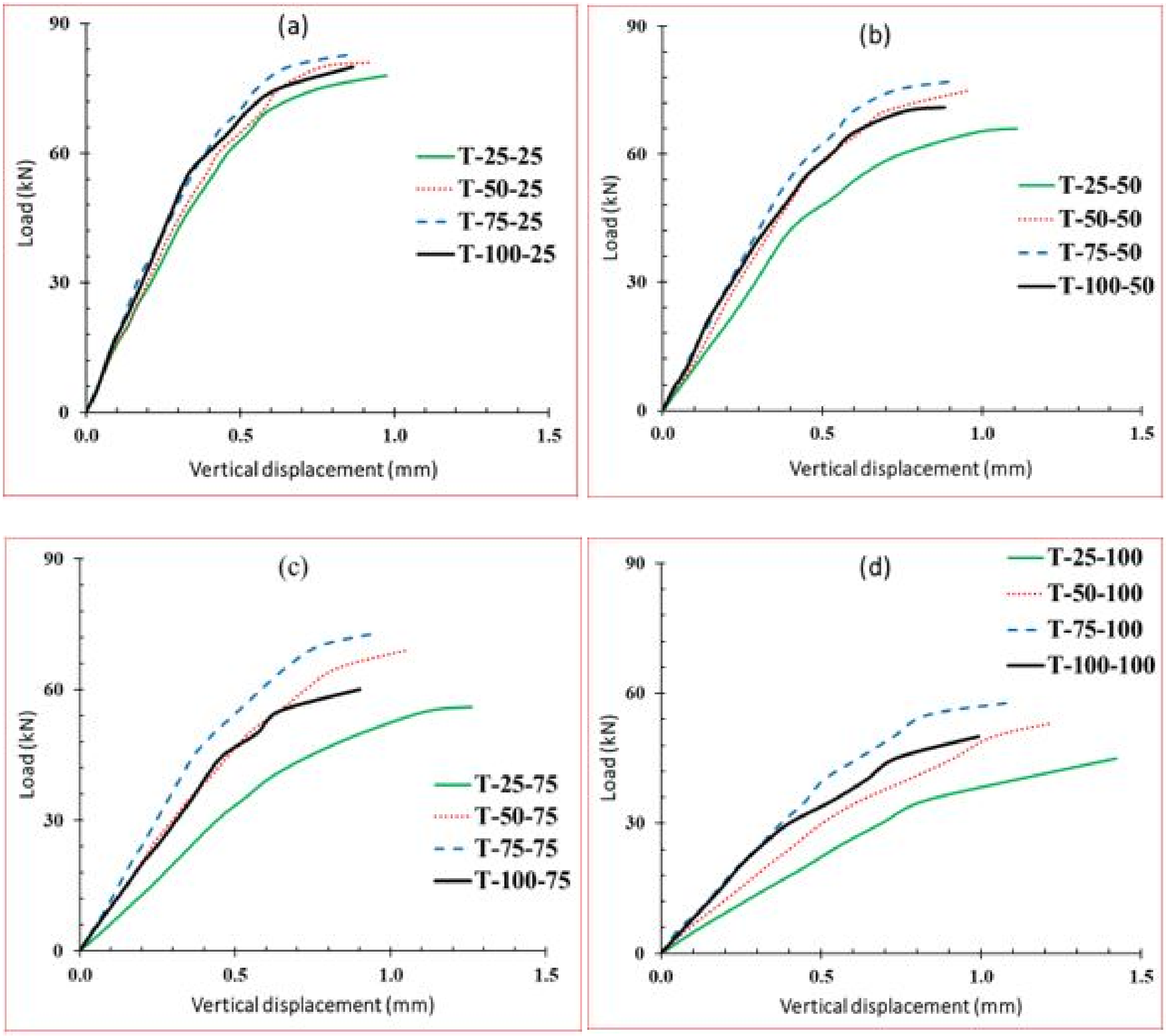

Fig. 4. Load –Vertical Displacement Response of Tree-Like Column: (a) Group 1, (b) Group 2, (c) Group 3, (d) Group 4.

of vertical displacement decreased between (5.9 - 31.3) %. Also, when the ratio of the specimen's width to total width increased, the amount of vertical displacement increased between (2.0 - 46.2) %. The vertical displacement of all specimens was higher than the vertical displacement of the reference specimen. The efficiency ratio was calculated for each specimen by dividing the failure load of the specimen to the failure load of the reference specimen. Where it found that the efficiency increased as the ratio of the branch's height to total height (HB/HT) increased and decreased when the ratio of specimen's width to total width (W/WT) increased. This increase may be due to the increase in the specimen's stiffness. All specimens have an efficiency of less than 100 %. The specimen's efficiency ratios are shown in Table 4.

3.4. Failure Mode

The failure mode was generally buckling for all specimens, as shown in Fig. 7. Also, it was buckling for a reference specimen. The failure mode can be expected for this type of structure. The previous studies focused on strengthening this structure by using more branches in the top of the tree-like structure, they suggested that depending on Finite Element Method analyzing, but in this study, the failure load improved by studying the effect of two factors. The first is the ratio of the branch's height to total height, and the other is the ratio of the specimen's width to the total width.

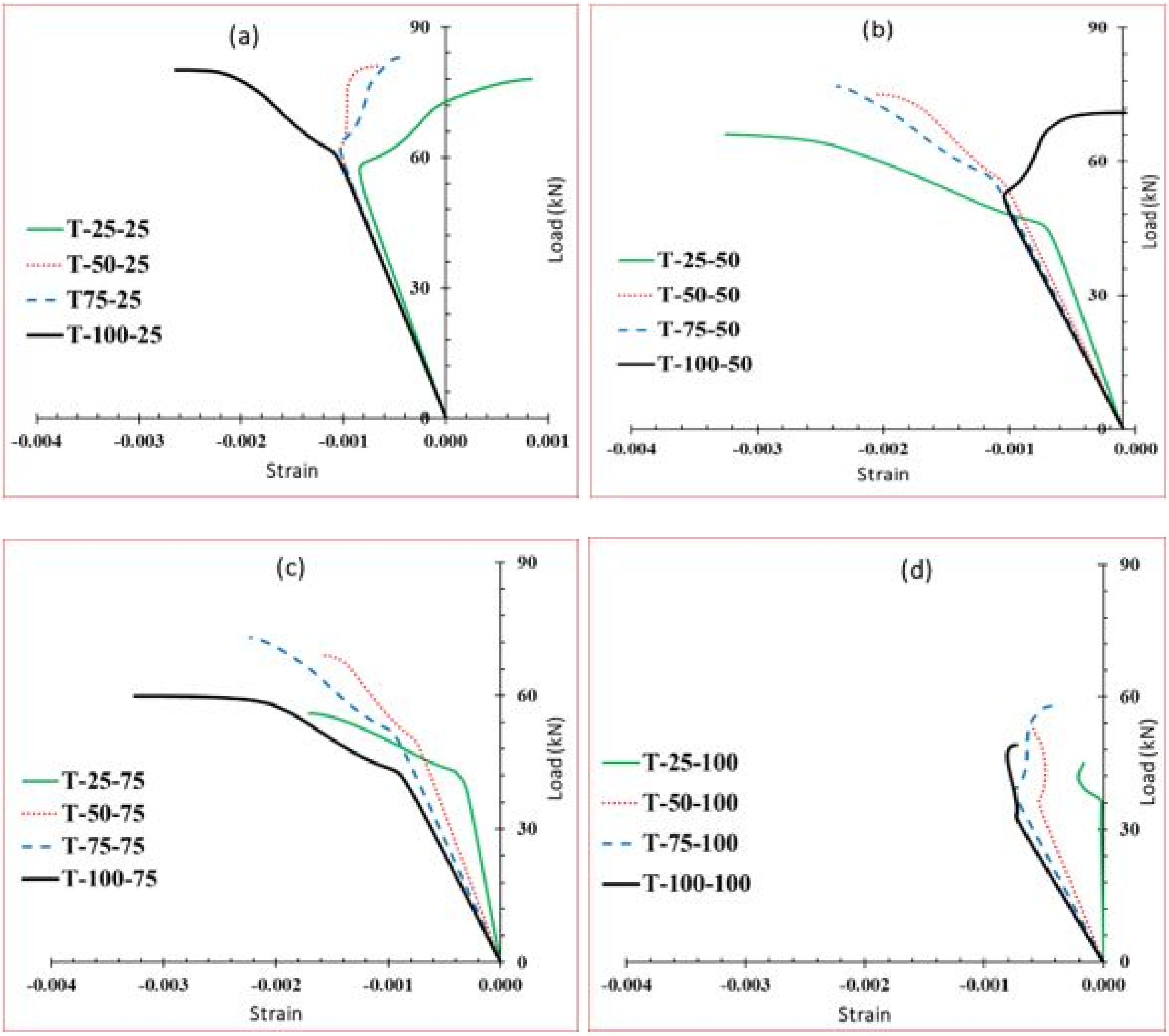

Fig. 5. Load –Strain Response of Tree-Like Column: (a) Group 1, (b) Group 2, (c) Group 3, (d) Group 4.

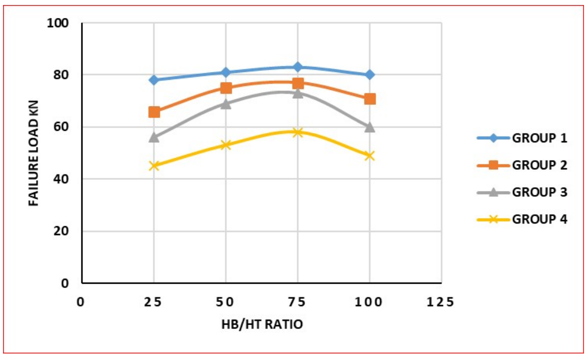

Fig. 6. Failure Load Versus HB/HT Ratio for Groups 1, 2, 3, and 4.

4. Conclusions

In this research, the results can be summarized as the following:

1. The failure load and buckling load of specimens increased when the branch's height to total height ratio increased until this ratio reaches (100 %), then the failure load and buckling load decreased. Also, the specimen's maximum vertical displacement decreased, and the stiffness of specimens increased when the branch's height to total height ratio increased.

2. When the specimen's width to total width ratio increased, the failure load and buckling load decreased, but the maximum vertical displacement increased largely, and the stiffness decreased.

(a) Groups 1.

(b) Groups 2.

(c) Groups 3.

(d) Groups 4.

Fig. 7. Failure Mode for Groups 1, 2, 3, and 4.

3. The load-vertical displacement curve became sharp, and the yield part was longer when the branch's height to total height ratio increased, but it became flat when the specimen's width to total width ratio increased.

4. Branching joint strain of specimens increased when the ratio of the branch's height to total height (HB/HT) increased; furthermore, it decreased when the ratio of specimen's width to the overall width (W/WT) increased.

5. All specimens failed with buckling mode.

6. The critical points of the tree-like steel column are the branching joint and the trunk for the case of two branches.

7. When comparing the research with previous research, we find that the study is new in terms of experimental testing of this type of structure. As previous studies focused on the theoretical aspect of the topic. Few researchers have touched on structural behavior and its effect on the external form, also previous studies did not discuss the effect of branch height to the total height.

8. It is preferable to construct the tree-like steel column with:

    (a) The ratio of the branch's height to total height (HB/HT) equal or less than 75 % to improve the stiffness and reduce the vertical failure displacement.

    (b) The ratio of specimen's width to the overall width (W/WT) equal or less than 50 % to reduces the decreases in stiffness because it has a significant impact on the behavior of the tree-like columns.

5. Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest..

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