DESIGN OF BEAM STRUCTURES WITH BRAIDED COMPOSITE TUBES

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SUMMARY: The purpose of this study is the establishment of designing method of FRP braided structures by using the Computer Aided Engineering system. The target is a scaffold made of CFRP braided composite tubes, all the dimensions of the scaffold is 450mm. The designing method includes the following 3 stages. In these stages, the stability, structural safety and material safety are checked by using the eigenvibration, buckling and static stress analyses, respectively. According to our concept, the most stable braided structure has the largest eigenfrequency among the proposed structures. The structural safety of the structure selected was checked by the buckling load. The material safety was checked by the comparison between composite tube strength measured and stress analysis results. Finally the scaffold designed by the proposed method was actually fabricated. The weight of scaffold fabricated by CFRP braided composite decreases by 71 percent in comparison with the conventional scaffold.

KEYWORDS: Scaffold, CAE system, Eigenvibration analysis, Buckling analysis, Safety factor

INTRODUCTION

The conventional scaffolds used in construction works are usually constructed by various steel components, however, that weight is heavy and the handling is a hard job. Stability, safety, low cost and light weight are required in designing scaffold. In order to satisfy these requirements, both the structural and material designing are needed. The scaffold must be taken to pieces and reassembled because of the easy transport. Therefore the scaffold must have some joints. In the previous studies[1]-[3] we have developed the fabrication techniques of complex braided composites with various three-dimensional shapes such as I-beam, T-shaped tube and so on. Braiding is one of the textile techniques to fabricate the preform with complex shapes. And braided preforms can be fabricated without cutting the fibers at connecting parts. These braided composites have superior mechanical properties.

In designing of composite structure, the various actual conditions, loading condition, boundary condition, environmental state, and so on must be exactly clarified. However it is usually difficult to predict these accurate conditions. This indicates that many experiments and trial manufacturings are required in the designing process. Accordingly the application of Computer Aided Engineering to the structural designing is effective. The purpose of this study is establishment of the designing method of braided composite structures, scaffold by using CAE system.

DESIGNING METHOD

The flowchart proposed in this study is shown in Fig.1. The designing method is subdivided into four stages. In the first stage, the whole scaffold geometry and some structures proposed which can be easily fabricated is decided. The scaffold designed in this study has a cubic shape, all dimensions is 450mm, as shown in Fig.2. The scaffold is composed of a top panel and a beam structure. The main target is the designing of the beam structure composed of straight tubes and T-shaped CFRP braided tubes. We set the designing condition that the beam structure can stand under the vertical loading of 980N on the top panel.

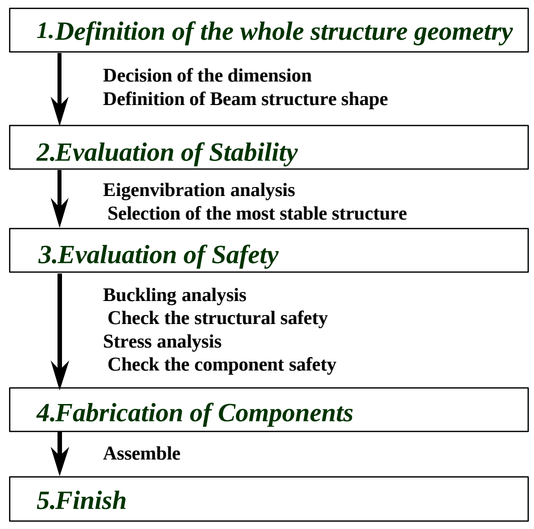


Fig.1 Flowchart of the proposed designing method

In the second stage, the stability of the beam structure is evaluated by using the eigenvibration analyses with various analytical conditions. As already mentioned, the actual loading and boundary conditions cannot be clarified. Namely stress values obtained from general static stress analysis cannot always correspond to that caused by the actual loading. The original application of the eigenvibration analyses to the evaluation of beam structure stability was performed. Generally, eigenvibration analysis is widely performed for preventing resonance. The eigenfrequency and the vibration mode of the structure can be predicted by using this analysis, when the geometry and the material property of structures are determined. It was defined that improvement of the stability was equivalent with increasing the stiffness in regard to the most deformable mode. The most deformable mode is equal to the 1st eigenvibration mode of the beam structure. The eigenfrequency related to the 1st eigenvibration mode is also correlated to the deformability. Namely the beam structure proposed with the highest 1st eigenfrequency has the highest structural stability. Based on the above analytical results, the most stable beam structure was selected in all the proposed structures.

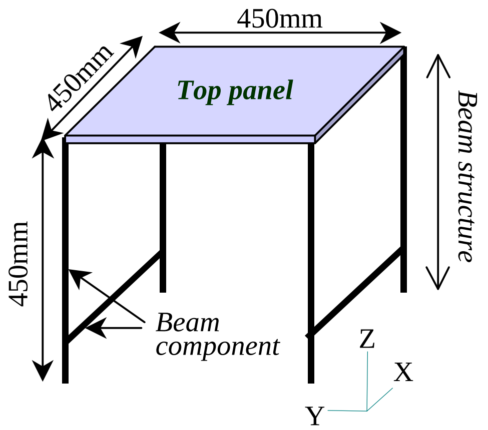


Fig.2 Geometry of the scaffold proposed

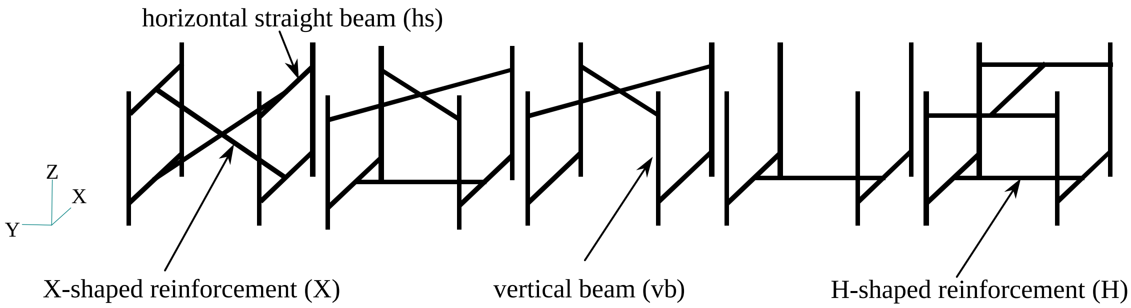
In the third stage, two kinds of safety of the beam structure selected with the highest eigenfrequency are checked. One is the structural safety, the other is the material safety. In the former, the buckling analysis was applied, and the safety was checked by comparison between the buckling strength and the virtual load, 980N. In the latter, general static stress analysis was applied and the stress values predicted in the beam structure subjected to the virtual load were compared with the CFRP braided tube strength measured. The safety factor was calculated from the component strength divided by the stress value. Here we set the safety factor 2.

In the final stage, two kinds of the beam components which satisfy the above safety was fabricated by the braiding machine. The scaffold finished was actually assembled.

EVALUATION OF STABILITY

Numerical Modeling

The beam structure is constructed by the straight and the T-shaped CFRP braided composite tubes. Both the braided composites are jointed together with a steel pin. In the eigenvibration analysis the cross-sections of the straight tube and T-shaped tube are constant, the inner diameter, outer diameter and the thickness are 17.5mm, 21.5mm and 2mm, respectively. In this analysis, beam elements was used because the outer diameter is enough small to ignore an overlization, as compared with the tube length. The material properties, E=50GPa, Poisson's ratio=0.4 and density=1.77g/cm^3 were used. These values are equivalent with the material properties of the general CFRP braided composite with Vf=44% and the fiber orientation angle 30 deg. In the second step, evaluation of stability, the numerical models corresponded to the above proposals are shown in Fig.3. In all the model, each component was devided into 6 beam elements.



Type-1	Type-2	Type-3	Type-4	Type-5
vb = 4	vb = 4	vb = 4	vb = 4	vb = 4
hs = 4	H = 1	hs = 2	H = 1	H = 2
X = 1	X = 1	X = 1		

Fig.3 5 types of beam structures proposed in this designing

Boundary Conditions

In case that the scaffold is actually used, the setting condition, mainly the friction with the floor surface is one of the most important factors. However the actual boundary condition cannot be also predicted. The boundary condition can make a great influence upon both the eigenvibration mode and eigenfrequency. This indicates that the application of various boundary conditions to the eigenvibration analysis must be considered. Various floor conditions are considered by changing the four constraints at the four floor contact nodes in analyses. In this study four types of boundary conditions were used as shown in Fig.4. Four boundary conditions, b.c.P, b.c.Z1, b.c.Z2 and b.c.Z3 correspond to all pin-supported, 2 diagonally pin-supports, 2 pin-supports and 1 pin-support, respectively. In b.c.Z1 toZ3, the translation in z-direction at other floor contact nodes are fixed. This indicates that the coefficient of friction between the scaffold and floor surface is decreasing in the order from b.c.P to b.c.Z3.

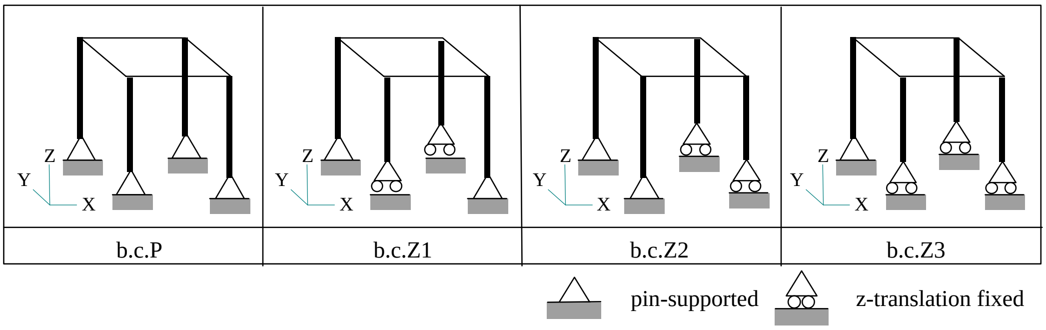


Fig.4 Boundary conditions correponded to various floor condition.

Analytical Conditions

In order to evaluate the stabilities of the above five structures, the following three analyses were performed. At first, the stabilities of beam structures were predicted under the four boundary conditions. Secondly the stabilities of the whole scaffold were simulated. In the second analysis, the top panel was modeled by using shell elements with 5mm thickness. Type-5 model used is shown in Fig.5. Young's modulus, Poisson's ratio and density used in the shell elements were 9.8GPa, 0.4 and 1.00g/cm^3, respectively. Thirdly the eigenvibration analyses considered the body weight, 980N were performed. This corresponds to the case that human with 980N body weight get on the top panel. In this analysis, the density of one shell element in the top panel model was set to 4.37E+3 g/cm^3. The mass of the high density element is equal to the virtual body weight, 980N. The numerical model used in the third analysis is same as Fig.5. Here, A to F denoted in the shell elements indicate the position of the high density element, Mass-A and -C correspond to the cases that human get on the top panel center and top panel corner, respectively.

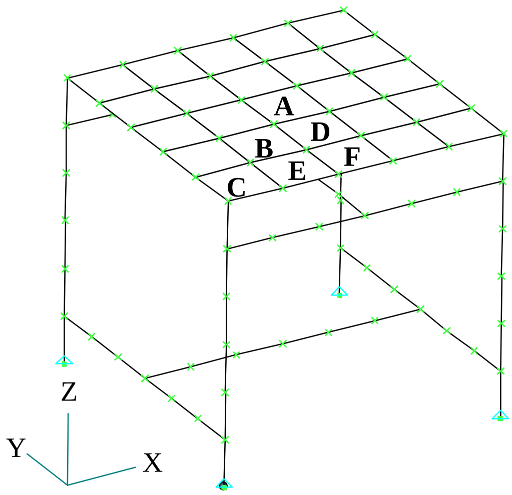
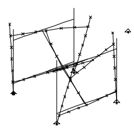
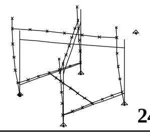
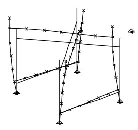
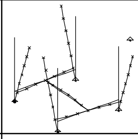
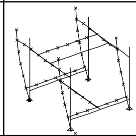
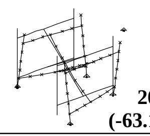
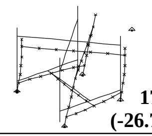
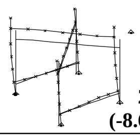
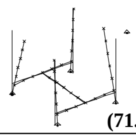
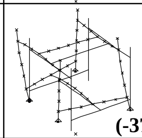
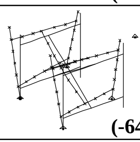
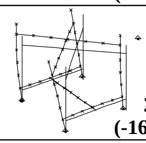
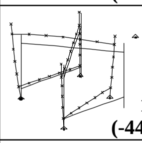
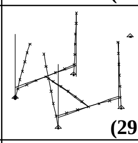
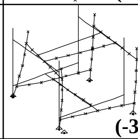
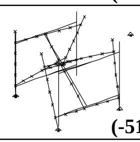
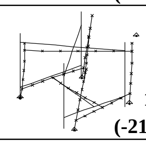
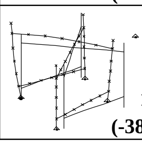
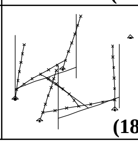
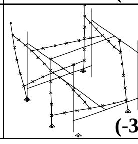


Fig.5 Numerical model of the whole scaffold used in the predictions of stability and safety

Analytical Reults

Table 1 shows the results obtained from eigenvibration analysis of the beam structure. In this figure, 1st eigenvibration mode and 1st eigenfrequency are listed. The values in parentheses denote the reduction ratio in the 1st eigenfrequency to b.c.P. It was confirmed that the most stable beam structure was Type-1 under b.c.P. However the eigenfrequencies under b.c.Z1, Z2 and Z3 were much smaller than that under b.c.P. This indicates that the stability of Type-1 depends upon the floor condition. On the other hand, Type-5 has the

Type / b.c.	Type-1	Type-2	Type-3	Type-4	Type-5
P	 55.05	 24.45	 23.48	 15.15	 44.91
Z1	 20.34 (-63.1°)	 17.91 (-26.7°)	 21.45 (-8.65°)	 25.94 (71.2°)	 27.98 (-37.7°)
Z2	 19.48 (-64.6°)	 20.40 (-16.6°)	 13.05 (-44.2°)	 19.66 (29.8°)	 31.38 (-30.1°)
Z3	 26.73 (-51.4°)	 19.23 (-21.3°)	 14.55 (-38.0°)	 42.52 (181°)	 27.40 (-39.0°)

unit :Hz

	Type-1	Type-2	Type-3	Type-4	Type-5
b.c.P	33.86	18.00	18.03	6.20	25.07
b.c.Z1	14.28	13.84	9.25	5.99	19.81
b.c.Z2	18.01	15.44	13.15	6.16	15.16
b.c.Z3	14.12	14.82	9.66	6.87	19.05

		Type-1	Type-2	Type-3	Type-4	Type-5
Mass-A	b.c.P	3.87	2.10	2.10	0.64	2.97
	b.c.Z1	1.85	1.68	1.16	0.63	2.43
Mass-B	b.c.P	3.44	2.06	2.06	0.64	2.88
	b.c.Z1	1.83	1.65	1.15	0.63	2.39
Mass-C	b.c.P	3.40	1.92	1.92	0.64	2.56
	b.c.Z1	1.80	3.08	1.13	0.62	2.25
Mass-D	b.c.P	3.78	2.06	2.06	0.64	2.91
	b.c.Z1	1.84	1.66	1.16	0.63	2.39
Mass-E	b.c.P	3.52	1.95	1.95	0.64	2.73
	b.c.Z1	1.80	1.60	1.14	0.63	2.29
Mass-F	b.c.P	3.45	1.94	1.94	0.64	2.58
	b.c.Z1	1.80	1.59	1.13	0.63	2.43

Unit : Hz

Table 2 shows the analytical results of the whole scaffold stability. Judging from Table 2, the similar results to the above was obtained.

The eigenvibration analytical results considered various weighting positions are shown in Table 3. In every type, the eigenfrequency of Mass-A is higher than other cases. When the human getting position is a center of the top panel, the scaffold stability is highest. The stability decreases with shifting the human getting position toward the corner. In this analysis, Type-5 constantly had the higer stability, as compared with other types. Judging from the above three types of analytical results, it was confirmed that Type-5 was the most stable beam structure.

EVALUATION OF SAFETY

Based on the above analytical results, the evaluation of safety of Type-5 was investigated. In this investigation, two types of analyses, buckling and stress analysis were performed. The buckling analysis was applied to the structural safety check because it cannnot consider the material fractures. The safety against material fractures was cheked by the stress analysis.

Structural Safety Analysis

The buckling analyses of Type-5 were carried out under b.c.P. The same material properties as the eigenvibration analysis were used. The numerical model was used, as shown in Fig.5. The loading condition was a face pressure loading. The six loading positions, A to F used are also shown in Fig.5.

Component Safety Analysis

In order to check the beam component strength, the stress analyses under b.c.P were performed by using the same model as shown in Fig.5. Three face pressure loadings at the A, B and C were respectively applied, the stress values were predicted. The total load is equal to the virtual load set, 980N. The component safety was checked by comparison between stress values obtained and strength measured.

Analytical results

For the evaluation of structural safety, the buckling analytical results are shown in Fig.6. The buckling mode as well as the buckling strength depends upon the loading position. From this figure, it was clarified that the maximum and minimum buckling strength were obtained from Load-A and –F, respectively. This indicates that the safety of the scaffold subjected to the loading at the center of the top panel is greater than the edge. However the minimum buckling load, 5.45kN was much larger than the virtual load, 980N. Namely it was confirmed that Type-5 had the enough structural safety.

Figure 7 shows the maximum stress value in principal beam components. It was confirmed that the dominat stress was a normal compressive stress caused in the vertical beam components. The stress occured in the vertical beam component C was important when the material strength was checked. The shear stress occurred in all beam components could be neglected. Namely stress in the vertical beams caused by the body weight could not be transmitted to parallel beam components with the floor. In this structure, bending moment occurred in joint area could be ignored. For calculating the safety factor, the stress-strain curves of three components, straight tube, straint tubes with steel pin and T-shaped tube under the unidirectional compression were measured. These curves obtained are shown in Fig.8.

The compressive strength of three components are 371.3MPa, 201.7MPa and 133.8MPa, respectively. The T-shaped tube is a weak point in the scaffold. Compared analytical results and experimental strength, the safety factor was 133.8/60=2.23. This result suggested that Type-5 was enough safe.

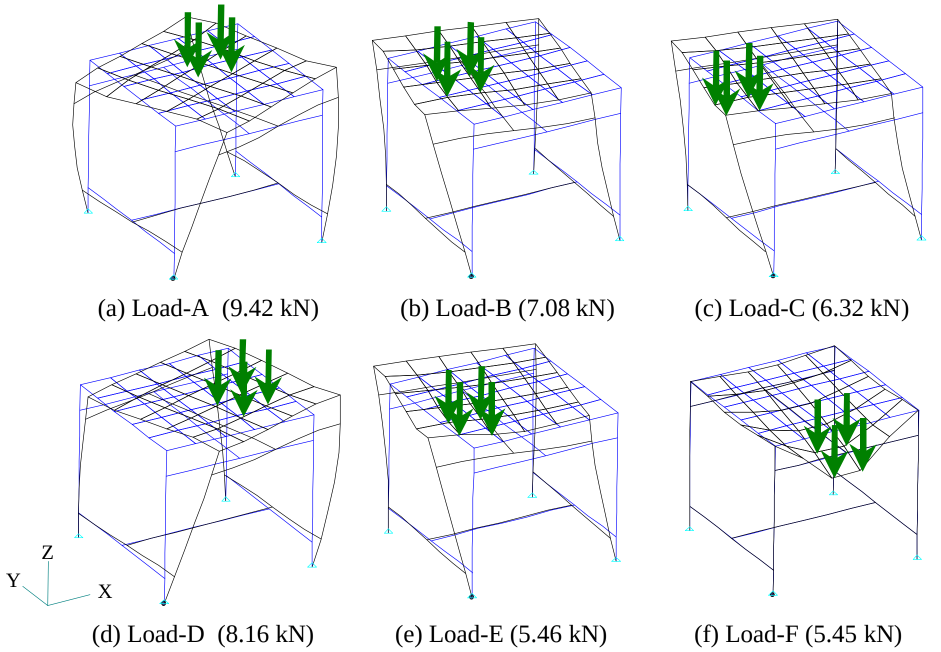


Fig.6 Buckling strength under 6 types of loading conditions

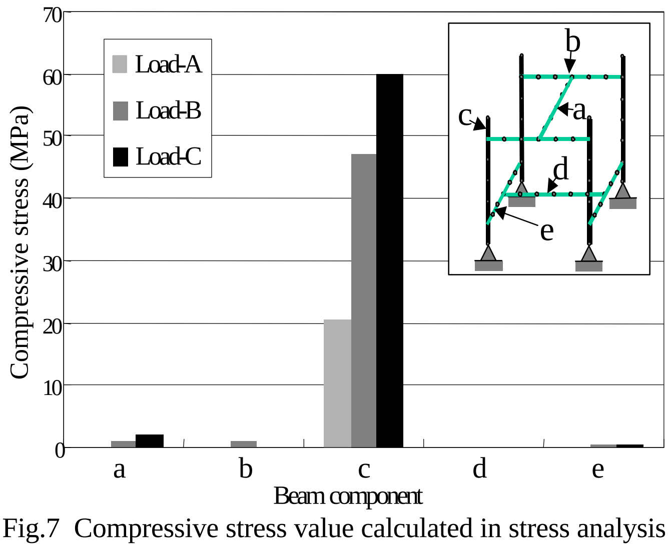


Fig.7 Compressive stress value calculated in stress analysis

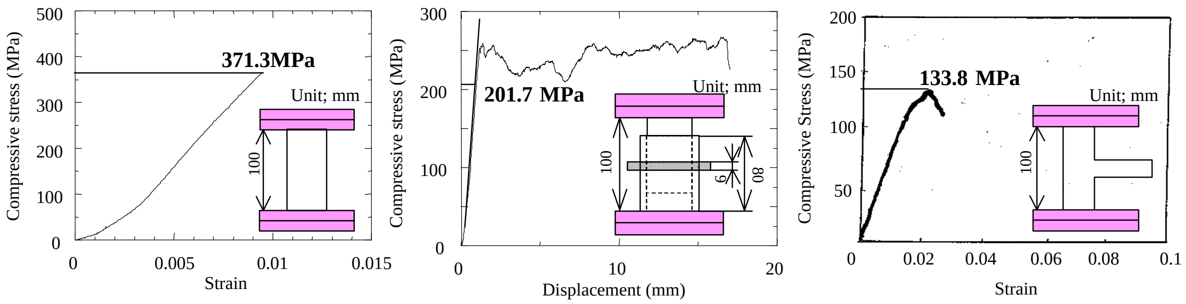


Fig.8 Stress-strain curves of three braided tubes obtained from axial compressive experiments

FABRICATION

Judging from the above all result, the fabrication of straint and T-shaped tubes were performed by using the braiding machine(Muratec Braider J-48, Muratec Corporation). In this fabrication fiber bundle was carbon fiber consisting 6000 filaments.(T300, Toray Industry Co., Ltd.) Matrix was epoxy resin (Epiclon, Dainippon Ink and Chemicals, INC.) and curing agent was amine system hardener (Epiclon B-857, Dainippon Ink and Chemicals, INC.) In the straight preform the braided angle which represents the fiber orientation angle to the longitudinal direction of the tube was 30 degrees. The straight braided tube had 3 layers. The outer diameter was 21.5 mm, and the nominal thickness was 2.0 mm. The fiber volume fraction of straight and T-shaped tubes was 44% and 56%, respectively. The T-shaped braided tube had 4 layers. The braided angle was 45 degrees, the outer diameter and the thickness were 25.5mm and 2.0mm, respectively. Each preform was immersed into resin bath in a vacuum container, and those preforms were cured in an oven at 100 for 2 hours. Figure 9 shows two types of braided tubes. The scaffold assembled by using these components is shown in Fig.10.

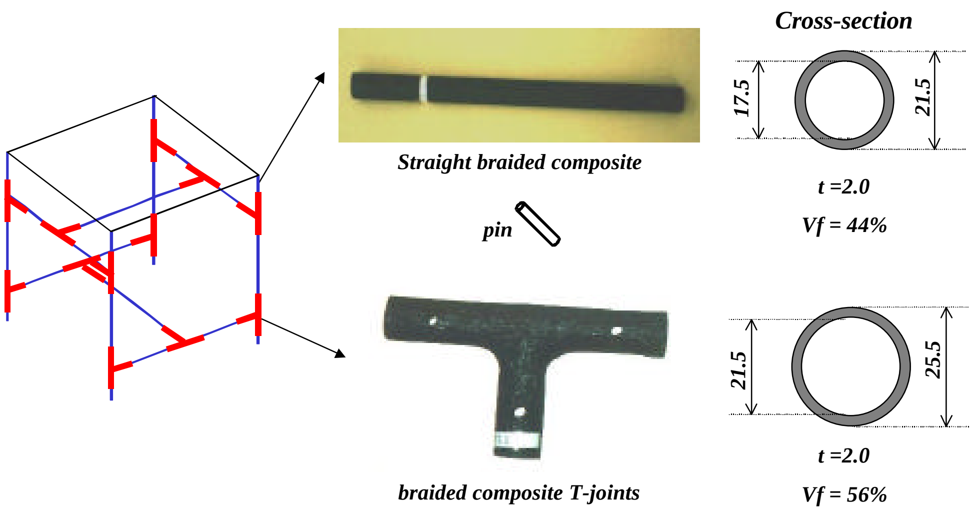


Fig.9 Photographs and cross-sections of CFRP braided straight tube and T-shaped tube fabricated

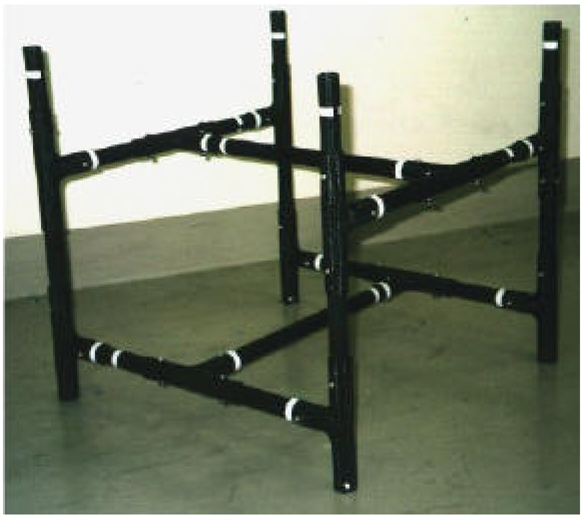


Fig.10 Photograph of the finished scaffold

CONCLUSION

The designing method for the braided composite structures were established and the scaffold were actually fabricated. The characteristic point to note in this method is that only CAE analytical approach without trial manufacturing is used in the designing. We confirmed that this method was effective for the shortening of development period and reduction of development cost.

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