-Technical Paper -

FUNDAMENTAL STUDY ON TP-CFRP CABLE FOR APPLICATION IN RC MEMBER

Hongyi LIN*1, Kazumasa OKUBO*2 and Junichiro NIWA*3

ABSTRACT

This paper presents a research conducted to study the mechanical properties of thermoplastic resin carbon fiber reinforced plastic (TP-CFRP) cables which will be used in civil engineering field. Three series of tests were conducted to evaluate the feasibility of TP-CFRP in practical application. The results showed that TP-CFRP has a higher tensile strength than steel bars. Besides, TP-CFRP could deform to anchorage hooks with certain strength inside concrete. And it was also clarified that the manual processing extremely affects the strength of TP-CFRP and it was quite sensitive to its structural integrity and the loading condition.

Keywords: thermoplastic resin CFRP, material properties, hook

1.INTRODUCTION

Since the first fiber reinforced plastic (hereinafter called FRP) footbridge in Harlingen in 1995 [1], FRP material has been used in civil engineering field for more than two decades. Because of its high strength and resistance to harsh environment and fatigue loads [2], FRP material has been usually used for external reinforcement in severe environment.

In addition, some of researchers planned to use the FRP as the main reinforcement of concrete [3]. But due to the limited operability of FRP, until now, there is few practical use of FRP as the main reinforcement of concrete.

As a kind of FRP, carbon fiber reinforced plastic (hereinafter called CFRP) inherits all merits of FRP and has a larger strength than the other FRP [4]. For the traditional CFRP which is consisted of heat-resist epoxy resin or BMI (Bismaleimide) resin, although both of them are used in aerospace industry, they are still too brittle to operate and expensive for civil engineering works.

In order to satisfy the requirements of operability and economy, the thermoplastic resin carbon fiber reinforced plastic (hereinafter called TP-CFRP) cable has been developed. The cable structure meets the needs of mild deformation and the thermoplastic resin gives the ability to deform at large angles after heating. Although TP-CFRP cables compromise on the strength in some degree, its cost reduction and operation enhancement fit the civil engineering field much better.

But as a new material, its fundamental properties remain unknown, so this paper presents a research conducted to study the mechanical properties of TP-CFRP cable in order to apply this material as reinforcement of concrete members as the replacement of steel in the future. This motivation means that the research needs to firstly, judge the possibility of TP-CFRP to be used as the structural reinforcement. Secondly, judge the performance of TP-CFRP under the requirements of deformation. Finally, the feasibility of the production and manufacturing process should be clarified.

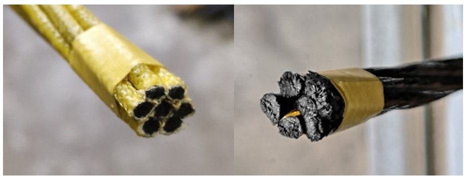
In this research, in order to achieve the motivation, following segmented experimental aims were raised: 1. To clarify the basic properties and processed properties of TP-CFRP, 2. To clarify the structural strength and appropriate parameters of the anchorage of TP-CFRP hooks.

2.TEST PROGRAM

2.1 Test material

The TP-CFRP cable used in this research is a kind of strand wire which is composed of 7 TP-CFRP wires. The pitch length of the strand wire is 300 mm, and the cross-section area is 42.1mm^2. Although there is no specific data of TP-CFRP, the information of the similar material called NH2437, which was used as external reinforcement of Zenko-ji Kyouzou in Nagano, could be obtained. From the data of NH2437, it can be assumed that the TP-CFRP is a light-weight and high-strength material. However, as shown in Figure 1, unlike NH2437 which has been used for external reinforcement in practice, the TP-CFRP is not covered by outer skin. Therefore, there are some different properties between two materials and one of them is that the cover used on NH2437 has poor resistance to alkaline environment. As a result, NH2437 is not suitable for practical use inside concrete so that in this series tests the TP-CFRP was used

*1 Graduate student, Dept. of Civil and Environmental Engineering, Tokyo Institute of Technology, JCI Student Member
*2 Senior Research Engineer, Kajima Technical Research Institute, Kajima Corporation, JCI Member
*3 Prof., Dept. of Civil and Environmental Engineering, Tokyo Institute of Technology, Dr. E., JCI member



a) NH2437 b) TP-CFRP

Figure 1 Two similar CFRP cables

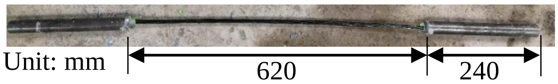


Figure 2 Size of the samples in material test

instead of NH2437.

2.2 Samples in Test of Basic Material Properties

The basic size of the samples used in this tensile test is shown in Figure 2. In this test series, all samples had an equal length of 1100mm and two 240mm steel pipes filled with resin were sheathed at ends to ensure that the sample could be fixed properly in the loading machine and there was no relative displacement between the steel pipe and TP-CFRP. Even subtracting the length of the steel pipes, the exposed part of TP-CFRP in the middle section was still longer than 600mm, which was twice the pitch length. All the test samples followed the requirements of JSCE-E 531-2010 standard[5].

In order to evaluate the influence of different processing on TP-CFRP, the test samples were divided into 5 groups according to the different processing and degrees. The specific groups and related processing conditions are shown in Table 1. There were 3 samples for each group. It is worth mentioning that originally, TP-CFRP cable was curved since it was rolled up for convenient transportation and storage.

The basic group used for blank control was STRAIGHTENED. Its comparison with the curved TP-CFRP could be used to prove the necessity of straightening operation. The comparison with the HEATED was designed to explain the influence of heating treatment on materials; the differences with RESTORED could clarify the influence of bending treatment on materials. And the comparison with TAPED, which used the tape to provide radial force in order to simulate the cover on NH2437, could prove the effect of radial force on material strength. In the manufacturing process of the RESTORED, the equipment used to bend the sample was the same as the equipment used in hook test and pull-out test mentioned later.

2.3 Samples in Hook Structure Test

Because the hook anchorage can make a full use of the advantage of the thermoplastic resin, so that clarifying the strength of the anchorage and determining the radius parameter of the anchorage hook is also the important objective in this research. This parameter will be essential in the process of stirrup production in the future.

In this test, due to the limitation of experimental equipment, the total length of the sample was increased to 2200mm and the bending start point was located in the middle of the sample. Similar to the previous sample, two 240mm steel pipes filled with resin were fixed at both ends.

Because there was no existing standard for hook of CFRP cables, the standard[6] of hook design for steel bar was referred to. In the standard of steel bar hook, the maximum hook radius was 3.5 times of the section diameter. Since TP-CFRP is a brittle anisotropic material, it is sensitive to the change of structure and shape, so that the strength decrement of TP-CFRP subjected to the deformation will be higher than that of steel bar. Therefore, as the first attempt, the radius of the hook was 74.4mm, which was four times of the cross-sectional diameter of TP-CFRP.

The samples and bending process are shown in Figure 3.

2.4 Samples in Pull-out Test

In order to clarify the actual anchorage performance of TP-CFRP hooks inside concrete structures, pull-out tests were carried out.

The design of specific pull-out test samples is shown in Figure 4. The total length of the TP-CFRP sample used in the pull-out test was 1100mm, and a 240mm steel pipe was sheathed at the outer end of the TP-CFRP. The parameters of TP-CFRP hooks in concrete were the same as those of hook strength test, whose radius was 74.4mm. The width of the concrete was 180mm, with 180mm height and 300mm length.

The design compressive strength was 30MPa and

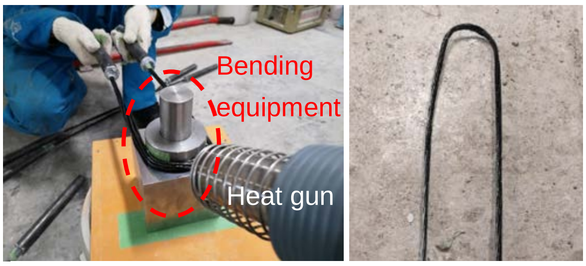


Figure 3 Bending process and a hook sample

Table 1 Process for different groups in material test

Group Name	Process
CURVED	No extra process
STRAIGHTENED	Straightened
HEATED	Straightened then heated for 1 min under 140 ℃
RESTORED	Straightened then bended to hook shape and restored under 140 ℃
TAPED	Straightened then covered by plastic tape

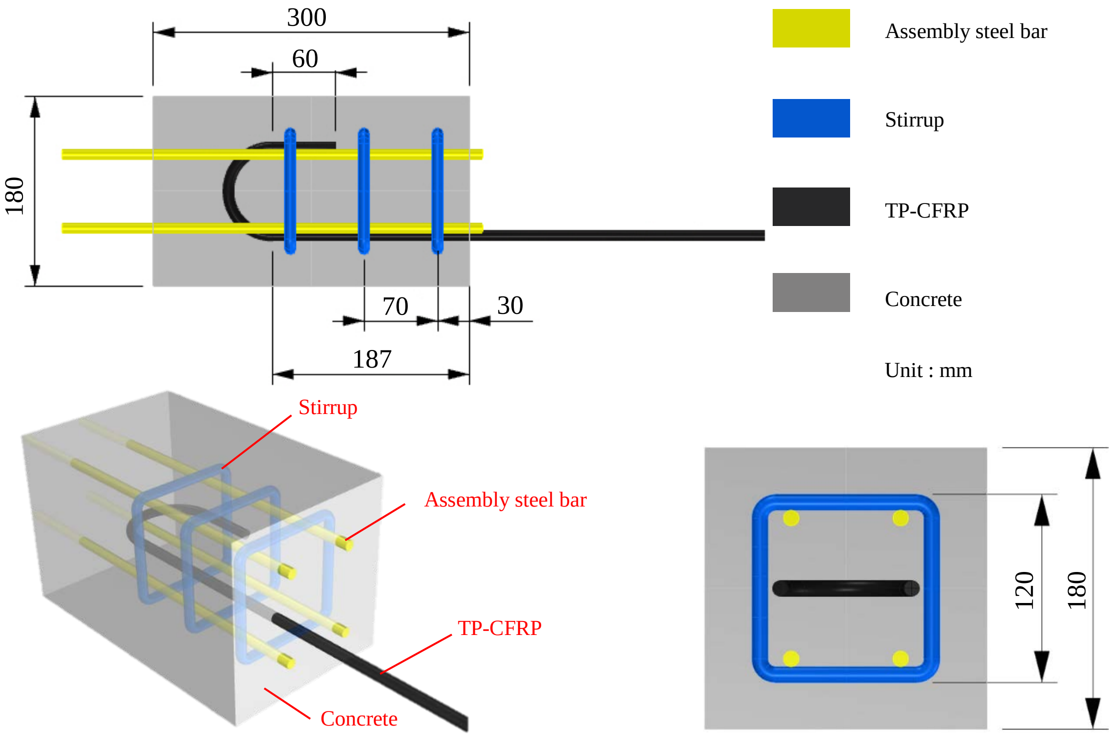


Figure 4 Design of samples in pull-out test

maximum coarse aggregate size was 20 mm. There were three stirrups to prevent the concrete from cone failure and four assembly steel bars inside concrete. The specimens were cured in moist condition for 7 days.

2.5 Loading Method and Instrumentation

All tests were conducted by using Amsler's universal testing machine shown in Figure 5 and all of them were vertical tensile tests with the two sides immobilization. Due to the different sample shapes, the fixation methods of the three tests were different, which are also shown in Figure 5 for details. The loading speed was 450N/mm^2 per minute following the JSCE standard[5], which is between 100 N/mm^2 and 500 N/mm^2 per minute. In all tests, there was no relative displacement between the sleeve and the inner TP-CFRP.

3.EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Test Results of Basic Material Properties

The specific test results of the five groups of TP-CFRP are shown in Figure 6. In all the cases, the tensile strength was more than 1250MPa and higher than the ordinary steel bars. Comparing the results of CURVED and STRAIGHTENED, it is found that there was large decrement without straightening. Although the CURVED was forced to straighten under a large tensile force in the test process, the results were not ideal. It can be seen that the process of heating with straightening from curved one (hereinafter referred to as straightening) is an indispensable step for the application of TP-CFRP.

Comparing the HEATED and STRAIGHTENED, it showed that if the time of heating treatment was so long that it would cause a certain impact on the strength of TP-CFRP although the average strength impact was less than 2%. Compared with the STRAIGHTENED, the strength decrement of RESTORED was about 16%, which was relatively intense. And it can be seen from Figure 7 that after the restoring treatment, a large number of visible defects appeared on the surface of the test sample, which were not only surface fracture but also thinning down of some parts.

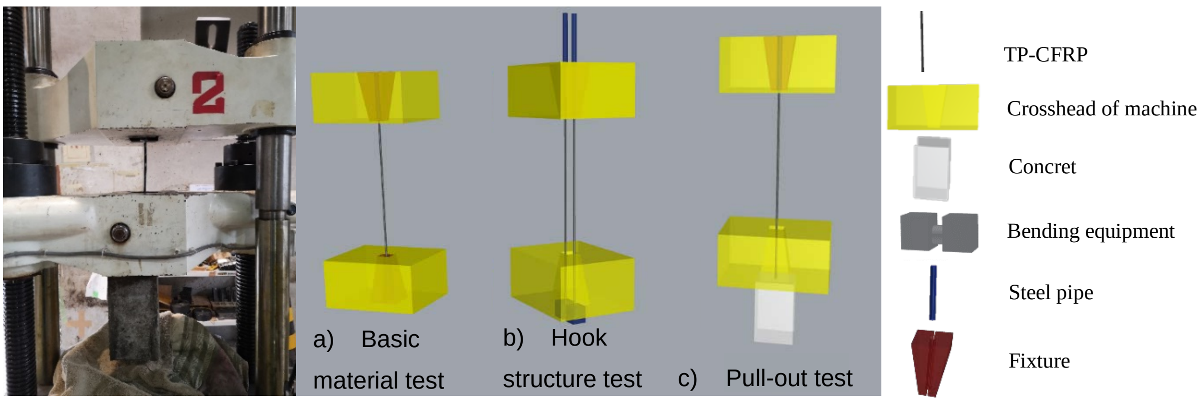


Figure 5 Loading machine and loading method for 3 different types of sample in article order

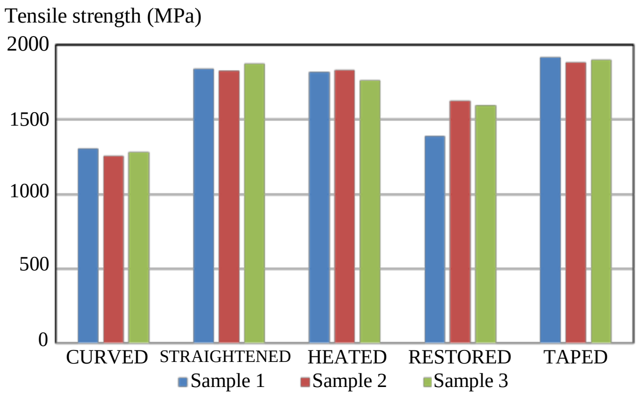


Figure 6 Tensile strength of samples

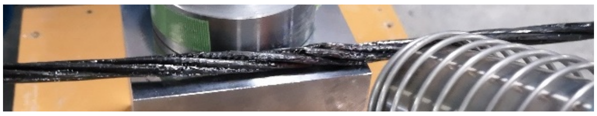


Figure 7 Surface of sample after restoring

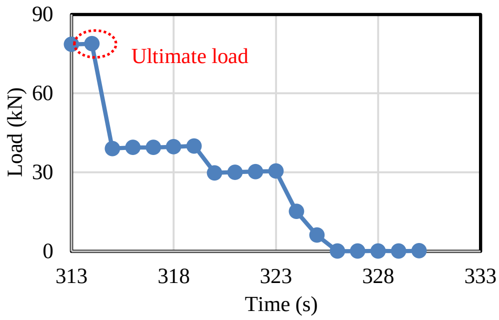


Figure 8 Time-load curve of STRAIGHTENED 1

During the whole restoring process, the heating temperature was around 140 ℃. Because of the property of thermoplastic resin, TP-CFRP almost lost its common mechanical properties under high temperature, with entering the softening state. So it can be assumed that TP-CFRP is not suitable for use in places with high temperature threats such as stokeholds or plants.

Taped CFRP had the highest tensile strength in this test, although the tensile strength provided by tape could be ignored. It can be speculated that the radial force provided by tape was the influential factor. As for the reason, there are two important factors. First, the radial force increases the stability of the structure. In the process of fracture, the separation between resin and fiber results in volume expansion. Obviously, the radial force will prevent this process. Secondly, because TP-CFRP is a brittle anisotropic material, the sensitivity to the direction of loading force makes it easily damaged when subjected to the eccentric force and stress concentration caused by the processing error. They result in local deformation, which will make the local loading condition even worse. The external binding force prevents the deformation of the local structure to a certain extent, thus effectively weakening the vicious cycle.

While concrete can provide more compact and comprehensive constraints for TP-CFRP, it can be positively guessed that this material should be able to achieve better performance inside concrete.

At the failure, except for the TAPED, the samples usually had 1-3 wires left after reaching the ultimate tensile load. The stress-time curve of TP-CFRP under overload condition is shown as Figure 8. It can be seen that the material still had potential in tensile strength and better safety for overload than a monolithic rod.

However, in the TAPED, all the strands were broken at the same time under the maximum load, so they did not have this property. This phenomenon can further prove that the radial force has a positive effect on the tensile strength by taking full use of the material potential.

As for the failure pattern, unlike the steel bar, the failure location of TP-CFRP was varied. Moreover, the failure sample was not simply split into two pieces just like steel bar. Sometimes a strand was broken into several pieces from different positions, which was quite different from traditional materials.

3.2 Hook Structure Test

The strength of the hook is shown in Figure 9 with the strength of other groups. The ultimate strength was lower than 50% of STRAIGHTENED. Even compared with RESTORED, it still decreased almost 41%. The reason for the strength decrement cannot be simply attributed to the hook structure, which will be explained below.

Firstly, from Figure 10, it can be seen that there were some structural defects on the finished hook, including uneven resin distribution and obvious discontinuities in the hook structure such as kick points. These caused the hook to be damaged easily and some defects finally resulted in the bending broken failure. From observation, it is likely that the bending fracture failure always happened in these discontinuities, which further indicates the stern requirements of TP-CFRP for

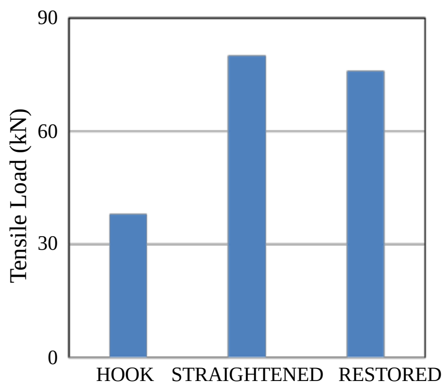


Figure 9 Average tensile load of samples

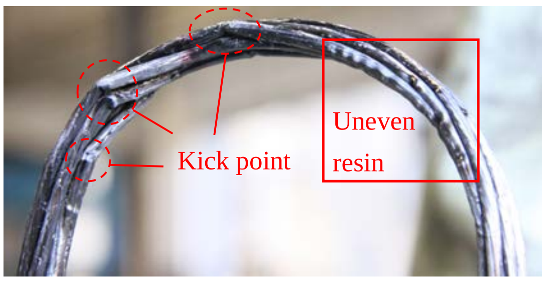


Figure 10 Defects on the hook

Figure 11 Failure of the hook

stress direction and structural continuity in practical use. In addition, the influence of these structural defects on the strength cannot be estimated, so that the complete attribution of the hook structure to this low strength cannot be clarified, either. Through the observation of the remaining hook part, there were usually 1-2 wires left after failure, which usually had better continuity and less structural defects. Therefore, it can be considered that the hook structure can perform better if there is no structural defect.

Secondly, limited by the loading machine, the sample length was different from the samples in basic material test and a 2200mm long sample was used. As a result, there were more deficiencies caused in the straightening process and the quality of the samples declines obviously. This is also an important point for the low strength of the hook.

Throughout all the failure pattern, the situation was very complex. As shown in Figure 11, not only the main failure in the hook structure, but also a lot of secondary failure in straight part occurred. It is speculated that the failure of the straight part might be caused by defects caused in manual process and the specific reasons need a further study.

Due to the influence of manual process, the evaluation of parameters in the hook design needs to be achieved by future research. However, this test exposed the problem that as a brittle and anisotropic material, TP-CFRP could not perform steadily under the practical manual process. Thus in TP-CFRP processing, stricter design, arrangement and operation are needed.

3.3 Pull-out Test

The results of three samples of pull-out test are shown in Figure 12. According to the different failure position, three samples will be divided into two parts for analysis.

As for sample 1, its failure position was located inside the concrete at almost the start point of the hook part. By comparing with the photo of the original hook, as shown in Figure13, it can be found that the failure happened at the first serious processing defect of the hook. As a result, the strength was relatively low. It further proves that solving the manual process problem is a key point to push TP-CFRP into practical application.

As for sample 2 and sample 3, the broken points were in the straight part outside the concrete. Compared with the previous tests, the maximum load in this test was far less than the ultimate tensile load of the STRAIGHTENED although they should be the same. And both of these two samples were 1100mm long, so that the effect of manual process should not be much different. From Figure 14, it is obvious that both of them are similar in failure mode which was bending fracture failure at the interface with pipe and middle area of straight part. So it is presumed that the results were caused by the offset of loading direction resulted from slight deviations of sample during loading process. In addition, the tough resin adhesive from pipe further damage the TP-CFRP after the loading angle occurs. It can be seen that TP-CFRP is sensitive to the direction of load.

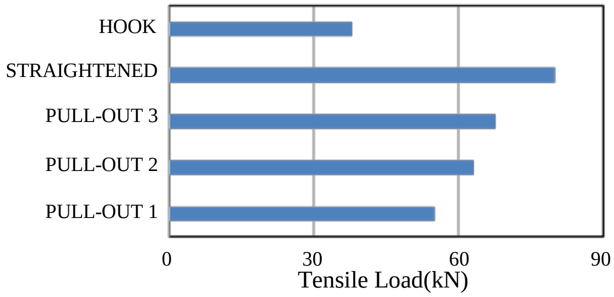


Figure 12 Maximum load of samples in pull-out test

a) Before casting b) After failure

Figure 13 the pull-out test sample 1

a) Sample 2

b) Sample 3

Figure 14 Failure of sample 2 and 3 in pull-out test

On the other hands, by comparing the results with those of hook tests, it is obvious that the performance became much better and shown its potential in practical use. It proves the possibility and feasibility of using TP-CFRP hooks as anchorage. Moreover, the binding force, radial force and the restriction on loading direction of concrete to TP-CFRP, will have a positive impact on performance of TP-CFRP inside concrete.

3.4 Comprehensive Analysis of Failure Mode

Take all three series tests into account at same time, a subtle relationship between the failure mode and the maximum tensile strength can be found, as shown in Figure 15. The failure states of different groups are arranged in the order of strength decreasing. It can be found that higher the strength was, less smooth the failure surface itself was, so that the failure was similar to the typical tensile failure in traditional impression. With the decrease of the strength, the failure surface became more smooth and sharper, which was more

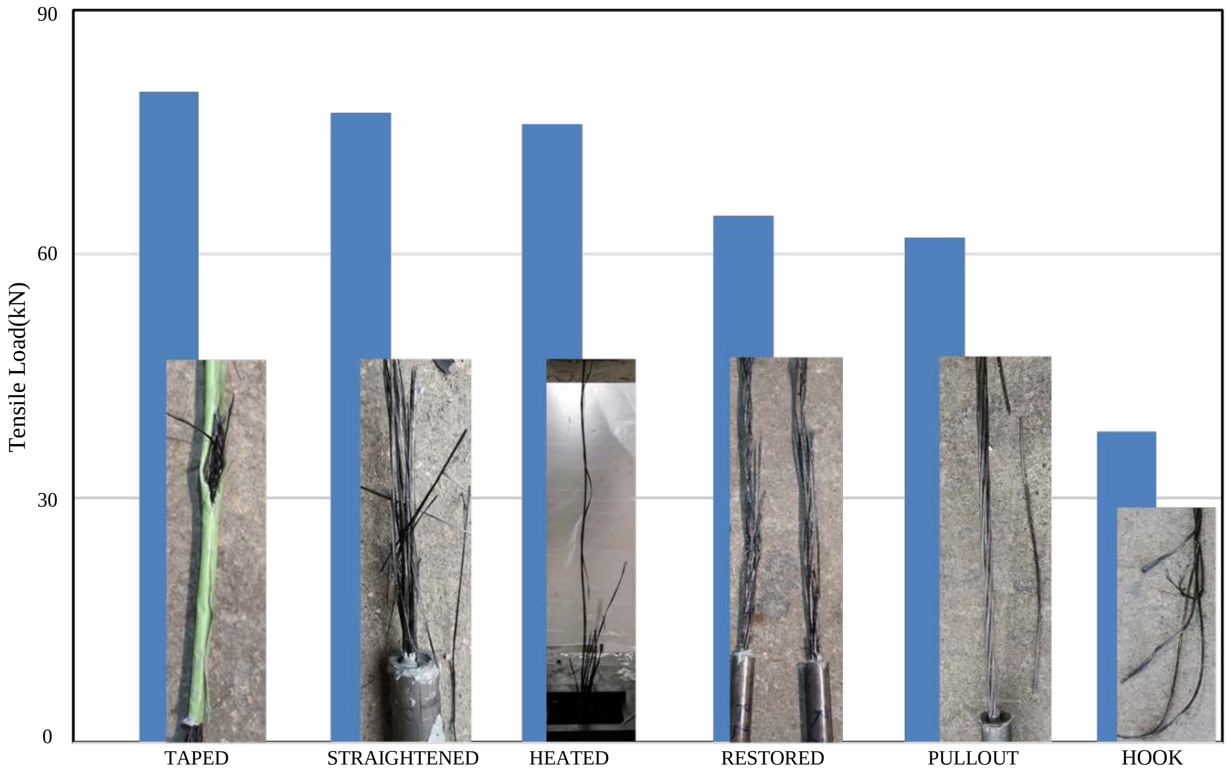


Figure 15 Failure and related ultimate tensile load (Unit: kN)

similar to the typical fracture failure.

As for the simple analysis, it is well known that TP-CFRP has higher strength in axial direction because of better utilization of fibers inside it, while only the resin can provide a slight bending and shear strength in other direction. Therefore, in the test group with full utilization of fiber strength such as STRAIGHTENED and TAPED, the results were better. On the contrary, in the test group with resin bearing extra load such as PULLOUT and HOOK, the results were relatively poor.

4. CONCLUSIONS

Based on the experimental results of three series tests, some of fundamental properties of the TP-CFRP material can be clarified and the following conclusions can be deduced in this study:

(1) Comparing the CURVED and STRAIGHTENED, it is necessary for the TP-CFRP to be straightened first then can be used in practice.

(2) From the result of STRAIGHTENED and RESTORED, it is found that the deformation treatment decreased 16% of strength. A series deformation treatment will cause the decrement of TP-CFRP strength so that it is not recommended to be reprocessed.

(3) Radial force affects the strength of TP-CFRP in a positive way from the result of TAPED, thus TP-CFRP is expected to perform better inside concrete.

(4) Defects caused in manual process affect the strength significantly, for the hook design, it is necessary to improve the production process.

(5) By comparing the results of pull-out test with those of hook tests, it proves the possibility and feasibility of using TP-CFRP hooks as anchorage.

(6) The TP-CFRP is sensitive to the structural integrity and the loading condition especially force direction. Its design standard and practical use should be more rigorous than those of the steel.

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