DEVELOPMENT OF ULTRA LIGHTWEIGHT HOIST ROPE OF TOWER CRANE FOR SUPER SKYSCRAPER

Sang Heon Lee[1]*, Song Soo Han[2], and Samyong Chung[1]

[1] *Construction Equipment Research Institute, Samsung C&T Corporation, Seoul, Korea*
[2] *Green Technology Research Institute, Samsung C&T Corporation, Seoul, Korea*
** Corresponding author (shlee31@samsung.com)*

ABSTRACT: Burj Khalifa, a skyscraper in Dubai, UAE, is the tallest man-made structure in the world. Its height reaches 828m but the taller super skyscrapers over 1 km have already been proposed. Tower crane is the key member for building such skyscrapers, which hoists heavy materials from the ground to the top of the construction site. The higher the building rises up, the longer hoist rope is needed and the weight of the rope gives burdens to the tower crane. The steel hoist rope, which was used for Burj Khalifa, weighs 6.32 kg/m and the total weight exceeds 5 tons when the crane climbs up to 800m. The crane has to lift not only the construction materials but also the hanging heavy rope. Therefore, the lighter and stronger hoist rope could provide a breakthrough in hoisting operation in super skyscrapers. A research on a novel hoist rope is on the way utilizing Dyneema, one of the UHMWPE (Ultra High Molecular Weight Polyethylene) fibers. They are the toughest fibers ever made and have usually been used in armor or mooring rope because of its lightweight, soft, and UV resistant property. Replacement of the steel rope with high strength fiber rope made of UHMWPE will reduce the weight of the hoist rope to about one-eighth, thus the load capacity of the tower crane could be drastically increased. This paper describes the design of the fiber hoist rope and the results of some performance tests.

Keywords: *Super Skyscraper, Tower Crane, Load Ccapacity, Fiber Hoist rope, UHMWPE*

1. INTRODUCTION

Successful construction of skyscraper can be made by proper and suitable combination of various construction technologies. A tower crane moving materials performs an essential role between them, because the period of construction can be reduced by the fast lift of many materials to the high place.

The highest skyscraper in the world, Burj Khalifa, has the height of 828 m. Even though the most of the programs were postponed or canceled due to the global financial debacle, new buildings higher than 1 km were planned for the past several years. It is still impossible to build these super skyscrapers with existing tower cranes used for Burj Khalifa, and new technologies are needed for the tower cranes building such super skyscrapers.

It cannot be a solution to increase simply the mechanical capacity of the crane because it would result in the heavier body of the crane and also the thicker structure of the

Fig. 1 World's tallest skyscraper Burj Khalifa

building suspending the cranes. It directly leads to a drop in profitability of the building construction.

Very simple and innovative method to improve the performance of the crane avoiding the above problems is the reducing weight of the hoist rope of the crane, since the weight of the hoist rope besides construction materials also puts a burden to the crane. The tower crane with 25 ton capacity used in construction of Burj Khalifa can lift full of its capacity at the nearest working radius but it can lift only 8 ton at the far radius of 52.5 m [1]. So it can lift only 2.7 ton of construction material except 5.7 ton of the steel hoist rope and the hook assuming the tower crane is at a height of 800 m. Therefore the construction of super skyscraper of 1 mile height by this crane will be tough work.

The weight of the hoist rope could be dropped drastically by replacing steel with super fiber. Super fiber refers the fiber out of common shows exceptionally high strength and elasticity.

The idea of ultra lightweight hoist rope made of super fiber is first proposed in 2007. The survey on super fibers was carried out for a year and UHMWPE (Ultra High Molecular Weight Polyethylene) fiber was finally selected as rope material because it is one of the toughest super fibers and its specific gravity is very low. The developed ultra lightweight hoist rope weighs about one eighth of conventional steel rope although it has the same strength. The first prototype sample was fabricated and tested at the construction site of Burj Khalifa in 2009. It was found that the fiber rope is sometimes wound up improperly on the winch drum because it has less lateral rigidity than a steel rope. Research was carried out to improve the lateral rigidity of the fiber rope and the second prototype was fabricated through several samples and tests. The winding up test of the second prototype was performed after the bending fatigue test. It was found that the feature of the second prototype was improved from the test.

2. SUPER FIBER

Super fiber shows extremely high strength compared to common fibers for clothes such as nylon or polyester [2]. It is mainly used as reinforcement for structural material these days, so that it is usually classified in high-tech industrial material other than fiber. The applications are aerospace, military, automobile, bicycle, sports, electronics, telecommunication, civil, construction and so on.

Super fibers are classified according to raw material and can be divided into two groups of organic and inorganic matters. There are 5 types of super fiber and the famous super fibers are aramid fiber for armor jacket and carbon fiber in composite materials for golf shaft and airplane body. The inorganic carbon fiber and organic aramid fiber

Classification		Strength (GPa)	Elasticity (GPa)	Elongation (%)	Density (g/cm^3)	Melting Point (℃)
Super fiber	Aramid	2.8	109	2.4~4.4	1.45	500~560
	UHMWPE	3.5	110	3.5	0.97	150
	Polyarylate	3.2	75	3.8	1.41	400
	PBO	5.8	280	2.5~3.5	1.56	650
	Carbon fiber	3.5	230	0.2~2.4	2.4~3.1	300~540
others	Steel	2.5~2.8	160~200	1.4	7.8	1150~1500
	Polyester	1.1	15	25	1.38	260

Table 1 Comparison of properties between the super fibers

account for more than 90% of world production. The remainders are UHMWPE, Polyarylate and PBO which are organic. PBO is most recently developed and shows notable features but the production is not enough to be used widely. Polyarylate rates somewhat superior to aramid in chemical and abrasion resistance and the applications are almost the same.

UHMWPE is made up of extremely long chains of polyethylene in the same direction and its molecular weight numbers in usually between 2 and 6 million, which is the origin of the name. It is widely used for mooring lines, tug rope, etc. because it floats and does not absorb water. The ratio of strength to weight is the best among super fibers so that it was selected as material of the ultra lightweight hoist rope. And also it shows several merits of high shock resistance, high abrasion resistance, high anti-corrosion and low friction but the melting point is lower than other super fibers.

The UHMWPE fiber used for the ultra lightweight hoist rope is Dyneema, which is the brand of fiber manufacturer, Royal DSM N.V. in Nerherland. DSM has the world's first patent on UHMWPE fiber and first started to produce it in 1990. The joint developer of the ultra lightweight hoist rope is DSR Corporation in Pusan Korea, which is one of major manufacturer of fiber ropes made of Dyneema.

3. ULTRA LIGHTWEIGHT HOIST ROPE

The ultra lightweight hoist rope made of Dyneema weighs about 1/8 of a conventional steel rope while the tensile strength is the same. The elongation before failure is about 4% and the elastic energy is extremely low. So it does not whip when it breaks while a steel rope does and it can cause a fatal accident. Dyneema is chemically stable and has high UV resistance so its properties are rarely affected by sunlight. The abrasion resistance and the low coefficient of friction also assure a long life of the rope.

3.1. First Prototype

The first prototype of the fiber rope consists of 7 sub-ropes laid on parallel and they are covered by a protecting jacket as shown in Fig. 2. Each sub-rope is made by braiding 12 strands of basic fiber rope.

The aim of the first prototype was the tensile strength of 130 ton and the diameter of 36 mm which are the specifications of the steel hoist rope of the tower crane used in construction of Burj Khalifa. The tensile strength of the prototype is 115 ton and the diameter is 36.7 mm. The weight is 82 kg per 100 m while the steel rope's weight is 632 kg.

The fabricated rope was tested at the construction site of Burj Khalifa. The rope was installed at a 25 ton tower crane and it repeated winding up and reeling out the fiber rope while the load acts 5.2 ton on the rope. The test items were proper winding up on the drum, problems of high speed winding up, friction between the rope and sheaves, rotation of the rope, sway of the rope by wind, and so on.

It was observed that the rope was not wound up properly after repetition of winding up and reeling out as shown in Fig. 3. The reason is the change of the rope section. The large tension of the rope in the upper layer on the drum acts compression on the rope in the lower layer along the

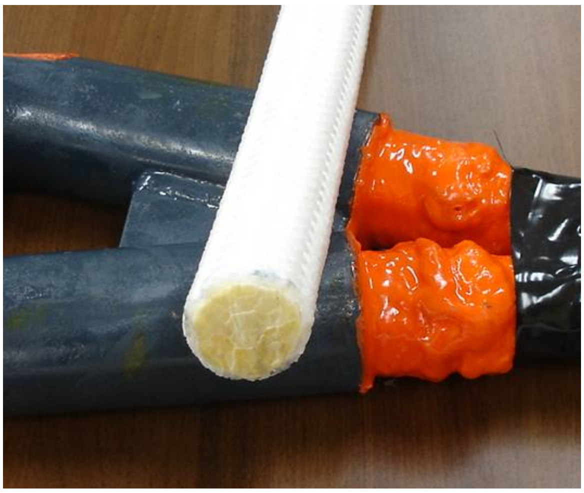

Fig. 2 First prototype of ultra lightweight hoist rope

direction to the drum center. The lateral compression made the rope section become an ellipse. The longer diameter of the fiber rope had gone up to 40 mm. It pushed the rope at the side and obstructed it from the even lay on the valley between ropes in the lower layer on the drum.

The fiber rope was easily distorted due to the lower lateral stiffness than the steel rope. The test at the laboratory reported that the diameter of the fiber rope changed by 22.2 % under 1 ton lateral compression while the steel rope changed by only 5.4 %.

3.2. Second Prototype

The development was carried out to reduce the section change of the fiber rope for the purpose of proper winding up. Numbers of samples were tried to verify the ideas to minimize deformation, and finally the insertion of nylon bar at the center of each strand have been selected for the second prototype.

The rope was made up by braiding 12 strands of 2 parallel sub ropes with a centered nylon bar and also inserting a thicker nylon bar at the center of the rope core as shown in Fig. 4. Its hardness was more strengthened by upgrading chemical filler and repeating the compression process twice before covering it with a jacket.

The second prototype fabricated has 26 mm diameter and it weighs 46 kg per 100 m while the steel rope of the same diameter has the weight of 287 kg per 100 m. The fiber rope breaks at 41.5 ton tension which is a little lower than the steel rope's tensile strength of 44.2 ton.

4. PERFORMANCE TEST

4.1. Bending Fatigue Test

A bending fatigue test was performed to evaluate the durability of the second prototype. The rope travelled 4.5 m back and forth through sheaves of 800 mm and 1,000 mm diameter in 4 cycles per minute. Any deformation or abnormality was not observed after 50,000 repetitions but the bumpy surface of the rope was found after 70,000 repetitions as shown in Fig. 5.

It was known from the test that the large sheave diameter and the equivalent size of a sheave groove can minimize the rope deformation.

Fig. 3 Improper winding of the fiber rope

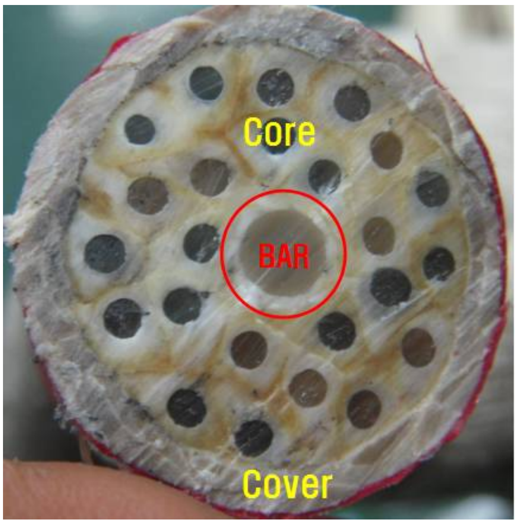

Fig. 4 Section of the second prototype

Fig. 5 Rope deformation after the fatigue test

4.2. Winding up Test

A winding up test using a crawler crane was performed in the field to check the possibility of the improper winding up and the set up is shown in Fig. 6. The crawler crane has a capacity of 250 ton and its winch system can pull up to 13 ton. The length of the rope sample was 300 m and 6 lines of ropes were fallen from the boom end to the hook block to secure the sufficient length of the rope's travel. The drum was modified for the rope to be wound up several layers on the drum as shown in Fig. 7.

The test load for the rope was varied from 0.3 ton to 10.2 ton and also the winding speed was also varied up to the maximum. The change of the diameter and the length were measured after every 10 times of loading.

3.3 ton tension made the length of the rope become longer by about 0.5 % but it was recovered directly within 0.02% elongation after unloading. The more repetition of loading and the larger tension exerted on the rope, the larger change of the diameter was made. The impactive increase of the load also deteriorates the shape of rope section. But the winding speed is not so influential in the deformation.

As expected, no deformation was observed at the portion which was not wound up on the drum but the lower layer of the rope experienced the more deformation of the section. Fig. 8 shows the trend of deformation with respect to layers. The eccentricity means the ratio of major and minor diameters, and 0 corresponds to a perfect circle. So we can naturally conclude that the direct cause of the deformation is the lateral compression on the drum brought by the tension of the upper layer rope.

Fig. 6 Crane setup for the winding up test

The first prototype was also tested under the same conditions to compare with the second prototype. The shape of the rope deformation is shown in Fig. 9. It can be known that the deformation of the second prototype was greatly improved compared to the first one.

Fig. 7 Rope reeled on the hook block and the drum

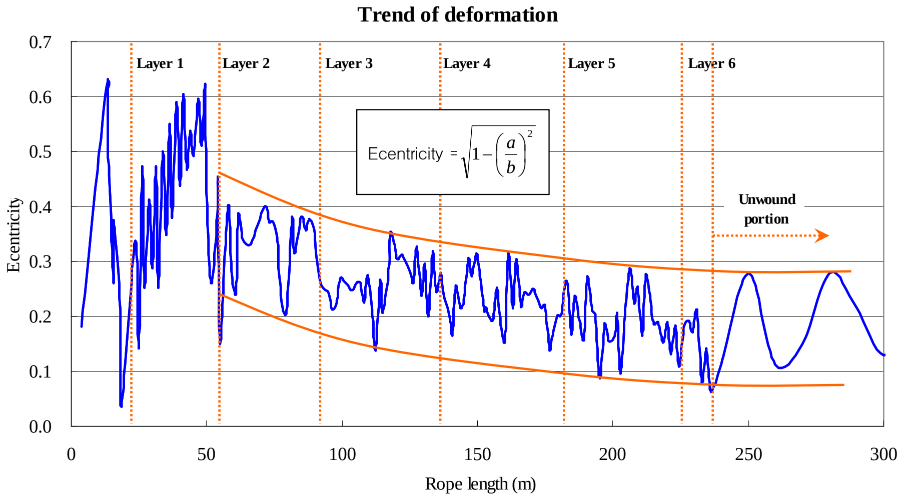

Fig. 8 Trend of deformation with respect to layers

5. CONCLUSION AND FUTURE WORK

The idea to increase load capacity of a tower crane for construction of a super skyscraper such as 1 km or 1 mile high building was proposed. It is the ultra lightweight hoist rope made up of UHMWPE super fiber, which has the weight of about one eighth of a steel rope. Two prototypes for the fiber hoist rope were fabricated and tested. The winding up test have shown that the rigidity of the second prototype was improved by inserting a nylon bar into each strand and the center of the rope. It is still needed to enhance the rigidity for practical application and development will be continued for commercialization.

And also another approach will be studied to utilize the pliable characteristics of the fiber rope. It is adoptation of a traction winch, which is generally used for a vessel or maritime machinery due to the capability accommodating large tension and huge length of a rope. The mechanism of a traction winch can make a sufficient tension at the end of the winch while it can wind up a rope on the drum under very low tension. So it is expected to be suitable for a winch system for the fiber rope.

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(a) First prototype

(b) Second prototype

Fig. 9 Deformation of the fiber rope after the test