Cyclic tensile tests of a quartz fiber cable assembly for a deployable antenna reflector on satellite was performed. The cable assembly showed non-linear tensile behavior in the first cycle, which caused large residual displacement after unloading. In the following cycles, relatively linear tensile behavior was observed as compared with that in the first cycle. Displacement at allowable maximum loading, however, increased in each cycle with increase of number of cycles. To study the causes of the non-linear irreversible tensile behavior, the quartz fiber cable assembly was divided into two parts, i.e. straight segment and loop segment, and those were tested individually. The straight segment showed non-linear tensile behavior in the first cycle and residual displacement after unloading. In the following cycles, almost linear tensile behavior was observed and incremental displacement was not developed. By contrast, the loop segment showed non-linear tensile behavior in the first cycle and residual displacement after unloading. In the following cycles, non-linear tensile behavior was still observed. Incremental displacement was almost same level with that of the cable assembly. The segment tests identified the causes of the non-linear irreversible tensile behavior of the quartz fiber cable assembly under cyclic loading.

**Key Words:** Quartz Fiber, Cable, Deployable Structure, Antenna Reflector

### 1. Introduction

A deployable large precise space structure is used as a high gain antenna reflector on communication satellites \(^1,\) 2) and radio astronomy satellites \(^3\). The antenna reflector should be folded to store in a nose fairing of launching rocket. Then, it is deployed to a required parabolic shape in orbit. The surface shape accuracy of the antenna reflector is important to fully demonstrate the designed frequency band.

Actuators are used to control surface shape of an antenna reflector after deployment. The actuator system, however, increases total weight of the antenna reflector, which requires a large payload rocket. To resolve the problem, cable/mesh system was adopted for the deployable antenna reflector on ETS-VIII and Astro-G program by JAXA\(^4\).

The deployable antenna reflector is composed of radial ribs and hoop cables. The hoop cables connect radial ribs. The radial ribs elastically deform by which a required parabolic shape of the antenna reflector is realized. The surface shape of the antenna reflector, therefore, strongly depends on tensile behavior of the radial ribs and hoop cables. The surface shape accuracy decreases by the folding and deploying action in the assembly process on ground and by aging due to environmental exposure in space.

A quartz fiber was used for the cable because of the low CTE and flexibility \(^5\). The quartz fiber cable has loop ends by which it is connected to radial ribs (hereafter the quartz fiber cable with loop ends is referred to as the cable assembly). The tensile behavior of the quartz fiber cable assembly should be well identified to assure the performance of antenna reflector.

In this study, tensile behavior of the quartz fiber cable assembly under cyclic loading was experimentally studied. Since the quartz fiber cable assembly showed non-linear irreversible tensile behavior, it was divided into two segments to identify the causes. Two segments were tested individually and then superposed the results to discuss whole response of the cable assembly. The segment tests revealed the causes of non-linear irreversible tensile behavior of the quartz fiber cable assembly under cyclic loading.

### 2. Experimental

#### 2.1. Cable assembly

A cable assembly is composed of twisted quartz fiber plied yarn (C9-33x8-S150-QS13, Saint-Gobain Quartz\(^5\)) as a load carrying material and Nomex knitted fiber tube as a covering material. The twisted quartz fiber plied yarn was composed of 8 single twisted quartz fiber yarns. Linear density of the single twisted quartz fiber yarn was 33tex and the twist level was 150turn/m. The quartz fiber was 9μm in diameter, 2.20g/cm\(^3\) in density and 78GPa in Young’s modulus.

In the actual antenna reflector, the cable assemblies are connected to cylindrical projections of radial ribs and carry tensile load to sustain the antenna shape. Cable ends were bended back and fixed by titanium clamp by swaging. Swaging of the titanium clamp was carefully performed by keeping maximum swaging load. Loop ends were made at both ends of a cable.

Three types of the cable assembly were prepared by changing the total length (L=100, 200, 300mm). Length of the loop segment was constant for all cable assemblies and only length of the straight segment was changed.
In general, pre-loading higher than maximum operating load was applied for genera-purpose steel fiber cable to remove looseness of each fiber. However, it was not performed in this study since it was not effective for the quartz fiber cable. Steel fiber deforms plastically by the pre-loading after which looseness of each fiber can be eliminated. By contrast, quartz fiber only deforms elastically since it was brittle material. The looseness still remains after pre-loading.

2.2. Cyclic tensile test

Cyclic tensile test was performed by a universal testing machine (STA-1150, A&D). Original test jig was attached to the testing machine to apply the tensile load to the cable assembly as shown in Fig. 1. The test jig had a loading pin of 3mm in diameter. Both loop ends of the cable assembly were connected to the loading pins.

Maximum load in the cyclic tensile test was 40N which was supposed as allowable maximum load for the cable assembly. Elongation of the cable assembly was measured by an eddy-current displacement sensor (EX-210, Keyence). Totally 30 cycles of the cyclic tensile loading was performed and load-displacement curve was obtained. The cyclic tensile tests were performed in the room temperature (≈20°C).

3. Experimental Results

3.1. Cyclic tensile test of cable assembly

Cyclic tensile tests of the cable assemblies of 100, 200, 300mm in length were performed with loading rate of 0.5mm/min. Loading rate was changed from 0.5 to 3.0mm/min and clear difference was not observed. Pre-loading of 1N was applied before the tests to straighten the cable assembly. Then, cyclic tensile test was started initializing the load to be 0N and the displacement to be 0mm.

Cyclic load-displacement curves of the cable assemblies are shown in Fig. 2. Non-linear load-displacement curves were observed in the first cycle for all cable assemblies. After unloading in the first cycle, large residual displacement was observed. The residual displacement was about 0.5 to 0.6mm which was not dependent on the cable length. This means that the residual displacement was mainly caused by the loop segments because the loop segment was the same for all cable assemblies.

Fig. 3(a) and (b) shows enlarged photos of a loop end at 1N loading and 40N loading respectively. The loop end was not fully straightened by 1N pre-loading. The loop end carries additional load with taking up the slack, which resulted in the non-linear tensile behavior in the first cycle.

By contrast, load-displacement curves were relatively linear in the following cycles as compared with that in the first cycle. The residual displacement was, however, increased with increase of number of cycles. Incremental displacement at 40N loading is shown in Fig. 4. The incremental displacement at 40N loading was calculated subtracting maximum displacement in the first cycle from maximum displacement in each cycle. The incremental displacement at 40N loading increased with increase of number of cycles and then saturated after some dozen cycles. Incremental displacement at 40N loading was not dependent on total length of the cable assembly. This result indicated that incremental displacement was also caused by the loop segments because the loop segment was the same for all cable assemblies.
3.2. Cyclic tensile test of each segment

The cable assembly was divided into two parts, i.e. straight segment (cable) and loop segment. Cyclic tensile tests were performed individually for the straight segment and the loop segment to identify the causes of non-linear irreversible tensile behavior of the cable assembly. Test condition was same as the cable assembly test.

3.2.1. Straight segment

A straight segment of 100mm in length was cut from the cable assembly. The straight segment was bonded to jigs of the universal testing machine using an epoxy resin as shown in Fig. 5. Since the cable soaked epoxy resin up by capillary action, cyanoacrylate adhesive was used to block the soaking.

Cyclic tensile test result of the straight segment was shown in Fig. 6. Here, the measured displacement was multiplied by an appropriate factor to reduce to the net straight segment length of the cable assembly of 100mm in length. It is directly compared to that by the cable assembly in the following chapter.

Non-linear load-displacement curve was observed in the first cycle. After unloading in the first cycle, residual displacement was observed. Incremental displacement at 40N loading was calculated from the load-displacement curve and the result is shown in Fig. 7. The incremental displacement at 40N loading was only observed in the first few cycles and did not increased with increase of cycles. In the first cycle, repositioning of the twisted quartz fibers may occurred, by which non-linear behavior and residual displacement was developed.

In the following cycles, the straight segment showed almost linear load-displacement curve except for the early stage of loading. In the early stage of loading, twisted quartz fibers were tightened up due to the twisted structure, by which slope of the load-displacement curve was gradually increased.

Tensile test of a Nomex knitted fiber tube was also performed to investigate the effect on the tensile behavior of the cable assembly. The Nomex knitted fiber tube was removed from the cable assembly and bonded to jigs of the universal testing machine using an epoxy resin. Length of the Nomex coating was 100mm. The load-displacement curve is
shown in Fig. 6. Here, the measured displacement was multiplied by an appropriate factor to reduce to the net straight segment length of the cable assembly of 100mm in length.

The test was stopped long before the load reached 40N since the Nomex knitted fiber tube deformed excessively. The Nomex knitted fiber tube does not have load carrying capability as compared to the twisted quartz fiber plied yarn.

3.2.2. Loop segment

Loop segment was cut from the cable assembly. Fig. 8 shows loop segment specimen for cyclic tensile test. Cut end of the loop segment was embedded into a partially hollow bolt and bonded using an epoxy resin. Cyanoacrylate adhesive was used to block the soaking of epoxy resin up to the cable before bonding. The loop end was hung to a loading pin on jig and another bolt end was connected to a testing machine as shown in Fig. 9. Cyclic tensile test result of the loop segment was shown in Fig. 10.

Non-linear load-displacement curve and relatively large residual displacement was observed in the first cycle. The causes of the non-linear load-displacement curve and the residual displacement is the same mechanism explained in chapter 3.1.

In the following cycles, load-displacement curve was still non-linear in the early stage of loading. Fig. 11 shows schematic diagram of the loop segment. Tensile load was applied by the loading pin to the loop end and transferred to the straight segment through the clamp. The clamp should be rotate to align the loading pass vertical. In rotating the clamp, the cable assembly cannot fully sustain load and then show non-linear load-displacement curve.

Incremental displacement at 40N loading of the loop segment with clamp is shown in Fig. 7. Here the incremental displacement at 40N loading was doubled since there were two loop segments in a cable assembly. Incremental displacement at 40N loading increased with increase of number of cycles and then saturated after some dozen cycles. The incremental displacement at 40N loading by two loop segments was much higher than that by the straight segment and almost same level with that by the cable assembly.
Fig. 12 shows stress distribution in the cable under tensile loading. Stress distribution in the cable is non-uniform in early loading cycles (Fig. 12a). Slip of fibers (pull out from the clamp) is locally developed, which is larger at inside of the loop and smaller at the outside. The local slip of fibers develops incremental displacement at 40N loading in the early loading cycles. After some dozen loading cycles, stress distribution becomes uniform (Fig. 12b) and incremental displacement does not increase.

To investigate the effect of clamp on the tensile behavior of the cable assembly, a loop segment without clamp was also prepared. The clamp was fully embedded into a partially hollow bolt as shown in Fig. 13, by which the effect of clamp on tensile behavior of the loop segment was eliminated.

Cyclic tensile test result of the loop segment without clamp is shown in Fig. 14. The slope of the load-displacement curve was larger than that of the loop segment with clamp. The slope was increased since the rotation of the clamp was eliminated. Incremental displacement at 40N loading is shown in Fig. 7. Here the incremental displacement at 40N loading was doubled since there were two loop segments in a cable assembly. The incremental displacement was slightly smaller than that by the loop segment with clamp. Although the effect of the clamp on the tensile behavior was eliminated, local slip of fibers (or pull out from the epoxy resin) was still occurred. Incremental displacement at 40N loading was, therefore, developed due to the loop configuration of the twisted quartz fiber plied yarn.

3.2.3 Comparison of cable assembly tests and segment tests

Load-displacement curves of the straight segment and the loop segment with clamp was superposed to compare to those of the cable assembly. A superposed load-displacement curve was obtained by summing straight segments test result (Fig. 6) and loop segment with clamp test result (Fig. 10), and the result is shown in Fig. 15. Here, displacement of the straight segment was multiplied by appropriate factors to be the net straight length of each cable assemblies of 100, 200 and 300 mm.
mm in length respectively. Displacement of the loop segment with clamp was doubled since the cable assemblies have two loop segments at both ends. The superposed load-displacement curves were almost coincided with those by the cable assemblies (see Fig. 2), by which the applicability of the segment tests was confirmed.

4. Conclusions

Cyclic tensile tests of a quartz fiber cable assembly for a deployable antenna reflector on satellite was performed. The causes of the non-linear irreversible tensile behavior were studied by the segment tests. The results obtained in this paper are summarized as follows.

1. In the cable assembly test, non-linear tensile behavior and residual displacement was significant in the first cycle. In the following cycles, load-displacement curve was relatively linear as compared with that in the first cycle. Incremental displacement at 40N loading increased with increase of number of cycles and then saturated after some dozen cycles.

2. In the straight segment test, non-linear tensile behavior and residual displacement was observed only in the first cycle, which was due to repositioning of the twisted fibers. In the following cycles, almost linear load-displacement curve was observed and incremental displacement at 40N loading was negligible.

3. In the loop segment with clamp test, non-linear tensile behavior and residual displacement was observed in the first cycle due to the slackness of the loop segment. In the following cycles, non-linear load-displacement curve was still observed due to rotation of the clamp. Incremental displacement at 40N loading increased with increase of number of cycles due to non-uniform stress distribution in the cable. The incremental displacement at 40N loading was saturated after some dozen cycles. The incremental displacement at 40N loading by two loop segment was almost same level with that by the cable assembly.

4. In the loop segment without clamp test, non-linear tensile behavior and residual deformation, incremental displacement at 40N loading was slightly decreased as compared with those by loop segment with clamp, which indicated the effect of clamp on the tensile behavior of the cable assembly.

5. The superposed load-displacement curves by the straight and the loop segment with clamp test results almost coincided with those by the cable assembly test results. The applicability of the segment tests was confirmed.

References


5) Quartzel brochure, Technical data, Saint-Gobain Quartz.