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Jacket effect on strain measurement accuracy for distributed strain sensors based on Brillouin scattering

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Fiber jacket has a function of protecting fibers from harsh environment; it also has an impact on the measured strain accuracy. In this paper, we report on our study of jacket effect to distributed Brillouin sensor system on strain measurement accuracy for constant load stretching and constant length stretching using the 900 μm tight-buffered fiber (Type-A) and the 250 μm optical fiber (Type-B). We have studied the time-varying performance under the stretching of constant load and length. It was found that, within 48 hours under constant load stretching, the strain value of the Type-A measured by BOTDR (Brillouin optical time-domain reflectometer) increased with time, while the Type-B it kept stable. Within 48 hours under constant length stretching, the strain value of the Type-A decreased with time, while the Type-B it kept stable. After relaxation, the strain value of the Type-B reached zero within 1 hour, while the Type-A declined gradually. We found the creep deformation and stress relaxation of jacket to be the leading cause to this phenomena.

Keywords: fiber optics sensors, Brillouin scattering, strain monitoring, jacket effect.

1. Introduction

In recent years, aging and overtime running of structures have become increasingly serious. As a result, the structural health monitoring (SHM) becomes an important research subject and advancement of intelligent sensing technology is the key to SHM. Because we do not know where the structures may have the problems, distributed sensing based on Brillouin scattering, such as Brillouin optical time-domain reflectometer (BOTDR), is the most promising technique for SHM [1, 2].

For distributed fiber sensor system, the fiber itself is a sensing medium that can be embedded in the structure that is sensitive to environmental changes. Therefore, protection of the optical fiber from damage and maintaining sensitivity of the fiber to strain and temperature are important issues. There is a trade-off between the strain sensitivity and protection for optical fibers.

Using the jacket is a feasible way of protection, and tight-buffered fiber coated with jacket is widely used in distributed fiber optic sensor. The jacket can transfer the physical quantities like temperature and stress [3]. Therefore, its performance indirectly determines the quality of fiber optic sensor [4]. Because the tight-buffered fiber is originally designed for fiber communication system rather than sensing, the jackets had introduced an extra strain uncertainty in strain measurement. In this paper we studied the impacts of two different jackets (normal bare fiber with 250 and 900 μm tight-buffered fibers) under the same strain for long-term stretching of constant load and length. The recovery process of the two optical fibers after relaxation is also compared in order to observe the jacket effect on the fiber optic sensor.

2. Experiment scheme

2.1. Experimental setups

Two experiments were designed to study the jacket effects over long-term: i) long-term stretching of constant load and ii) constant length stretching.

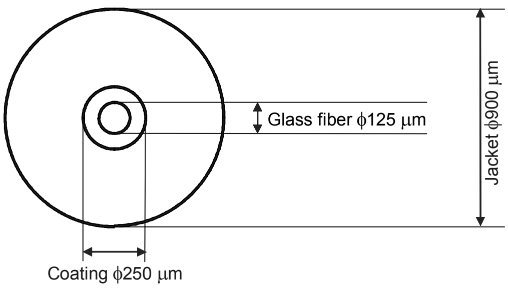

Fig. 1. Structure of optical fiber.

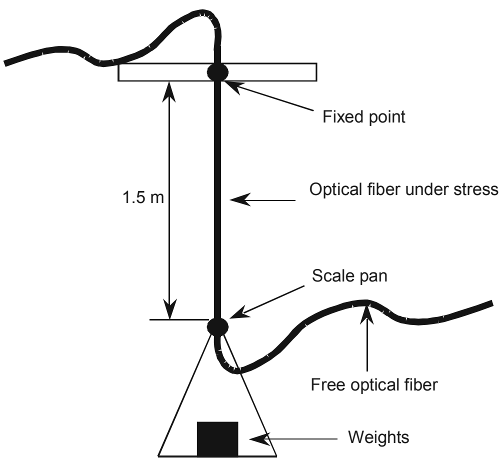

Fig. 2. Laboratory rack for constant load stretching of optical fiber.

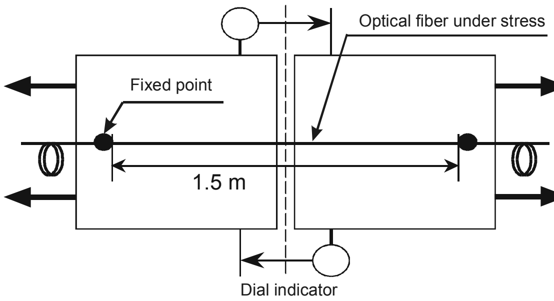

Fig. 3. Laboratory table for constant length stretching of optical fiber.

We selected two types of coatings for SM optical fibers. One is 900 μm tight-buffered fiber (Type-A), and the other is 250 μm optical fiber (Type-B), both being shown in Fig. 1. Type-A has one extra layer coating made of TPEE.

Two experiments were designed to study the time-varying performance of the optical fibers under the stretching of constant load and length, *i.e.*, laboratory rack for constant load stretching and the laboratory table for constant length stretching.

Figure 2 shows constant load stretching on the laboratory rack; one end of the optical fiber was fixed at the top of the rack using epoxy adhesive, the other end was fixed to a scale pan with certain weight, which produced invariable stress on the optical fiber. The length of the stretched fiber between the two fixed points was 1.5 m, which was longer than the minimum spatial resolution of BOTDR (*i.e.*, 1 m) – see Fig. 2.

Figure 3 shows constant length stretching. An optical fiber was fixed at two ends of the two lab tables using epoxy adhesive. The initial distance between the two fixed points was 1.5 m. The optical fiber was loose at first. By increasing the distance between two tables we can stretch the optical fiber.

2.2. Measurement principle

The principle of the measurement is that the light launched into optical fiber produces Brillouin scattered light, and Brillouin frequency shift changes linearly with strain and temperature. Due to the sensitivity of the Brillouin scattering sensor to both strain and temperature, the thermal compensation is required if the strain measurements are performed in an uncontrolled temperature environment with high strain measurement accuracy. A simple compensation technique using a temperature measurement fiber section loosely placed near the stressed fiber was applied [5], and the strain of optical fiber is given by:

$$\varepsilon = \frac{\Delta \upsilon_B}{\upsilon_B(0) \times C} = \frac{\upsilon_B(\varepsilon) - \upsilon_B(0)}{\upsilon_B(0) \times C}$$

where $\upsilon_B(\varepsilon)$ – Brillouin frequency shift with a strain, $\upsilon_B(0)$ – Brillouin frequency shift without a strain; C – coefficient of strain and ε – strain. The measurement is taken at room temperature.

The basic parameters of BOTDR are: pulse width 10 ns, spatial resolution 1 m, strain measurement accuracy $\pm 40\mu\varepsilon$, minimum distance range 1 km, maximum sampling points 20000, readout resolution 0.05 m [6].

2.3. Monitoring scheme

In constant load stretching experiments, the Type-A and Type-B were fixed to the laboratory rack. Different weights (50, 100, 200 and 500 g) were put into the scale pan in 4 groups. The strain was measured before the loads were used as reference. We measured the strains every two hours for 48 hours for the same load in order to see jacket effect over long-time. Then load was removed to let the fiber relax for 24 hours. During the 24 hours, we continued to monitor the fiber strain. Then we conducted second load for the same 48 stretching and 24 hours relaxation experiments. Such experiments were repeated for both fiber jackets.

In constant length stretching experiments, as shown in Fig. 3, the Type-A and Type-B were fixed at the lab tables. Increasing the distance between two tables and fixing them there after, we maintained the stretched fiber length at strains of $500\mu\varepsilon$, $1000\mu\varepsilon$, $2000\mu\varepsilon$, $4000\mu\varepsilon$. Similarly to the experiments of constant load stretching, the fiber was stretched for 48 hours and relaxed for 24 hours in one cycle; the experiments were repeated for four strains mentioned above.

2.4. Monitoring results

Figure 4 shows the strain distribution of optical fiber measured by BOTDR for Type-A fiber.

Due to the 1 m spatial resolution of BOTDR, there was only about 0.5 m wide flat strain on the strain distribution, this peak strain value reflects the real strain experienced by 1.5 m optical fiber. Because the distance between two sampling points

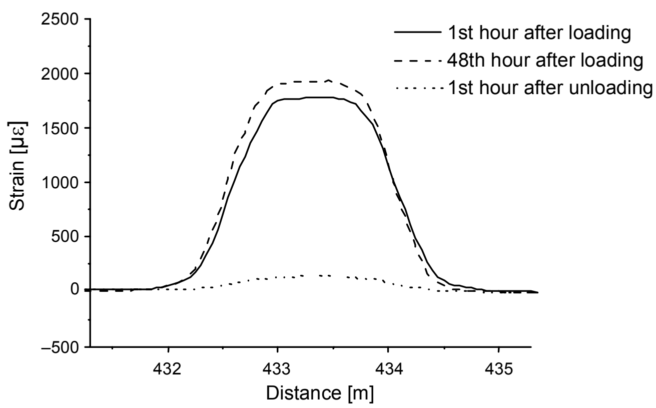

Fig. 4. Strain distribution lines of the Type-A under constant load stretching.

was 0.05 m, there were 10 continuous sampling points located at maximum strain, so the real strain value could be obtained by averaging the strain values of the 10 points [7–9].

2.4.1. Experiments for constant load stretching

Figure 5 shows the strain value of the Type-A over time. According to the strain measurement accuracy of BOTDR, the two dashed lines were plotted to present the strain accuracy where most of the points were located in the range.

The fit line shows that the strain value increased with time and the load, and the slope of the curves varies with the loads, *i.e.*, within 48 hours, the strain value of the group under heavy load increased faster than the one under light load (see Fig. 6).

Figure 7 shows the strain value of the Type-B over time. Unlike the Type-A fiber, the strain varies very little with the constant load over 48 hours.

Due to the weak protection of Type-B fiber, delamination occured at the interface between coating and cladding in the optical fiber for 500 g load due to overloading. No experiment was carried at this weight.

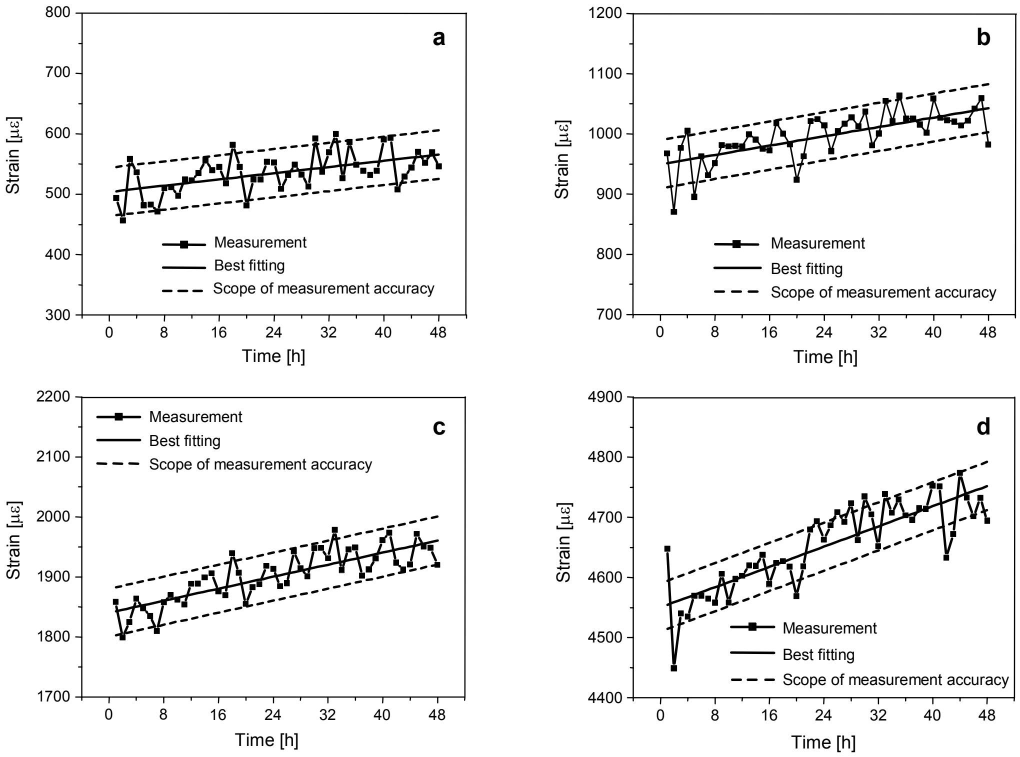

Fig. 5. Strain value of the Type-A changed with time under constant load stretching, 50 g (**a**), 100 g (**b**), 200 g (**c**) and 500 g (**d**), within 48 hours.

After 48 hours load, the weight was removed, the optical fiber was relaxed. Figure 8 shows the measured strain over time for 24 hours with Type-A and Type-B. It is clear that the strains in Type-B fiber show little change with time.

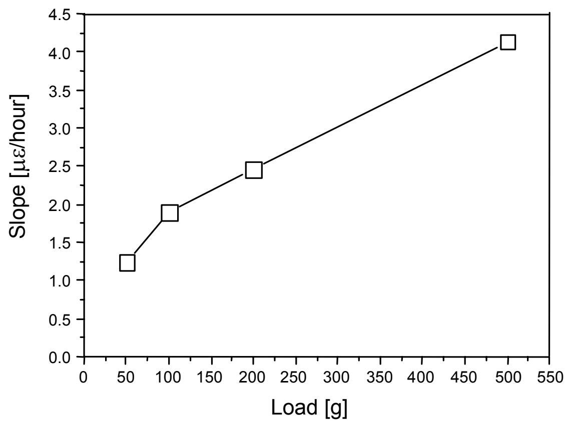

Fig. 6. Slope of the curves in the experiment for constant load stretching within 48 hours.

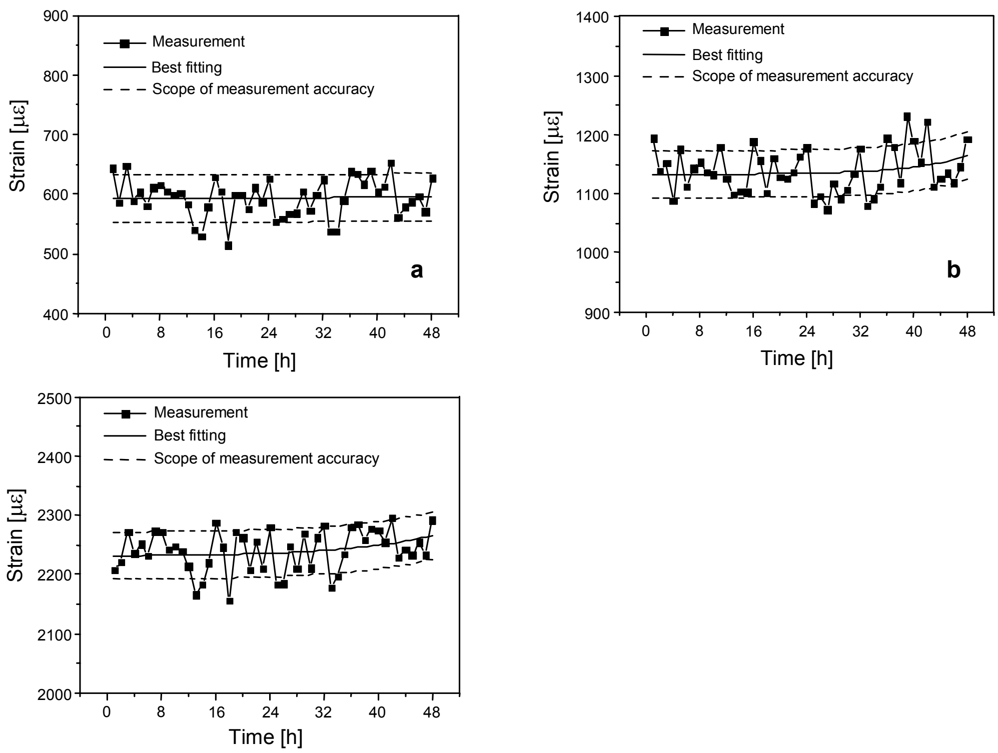

Fig. 7. Strain value of the Type-B changed with time under constant load stretching, 50 g (**a**), 100 g (**b**) and 200 g (**c**), within 48 hours.

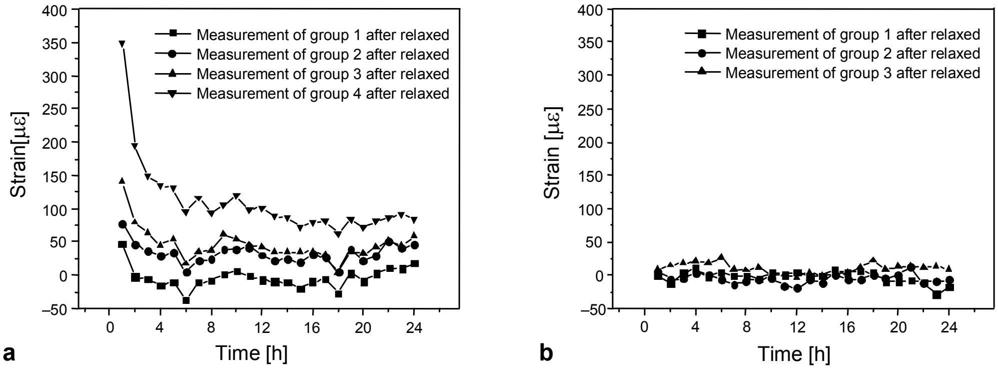

Fig. 8. Strain values of the Type-A (**a**) and Type-B (**b**) changed with time within 24 hours after being relaxed from constant load stretching.

All the strain values of the Type-B in the 3 groups reached zero in the 1st hour and then were kept stable. But the strain values of the Type-A in the 4 groups decreased gradually, and the strain value of the group under heavy load could not reach zero even 3 days later.

2.4.2. Experiments for constant length stretching

Within 48 hours, under constant length stretching, the strain values of the Type-A in four groups decreased slightly to the same degree (see Figs. 9 and 10).

As shown in Fig. 11, the strain value of the Type-B remained stable under constant length stretching within 48 hours.

After relaxation, the strain values of the Type-A and Type-B showed similar trends as those in the experiment for constant length stretching as shown in Fig. 12.

3. Analysis

According to the shear lag theory proposed by Cox in 1952 [10] the axial load on unidirectional composite materials produces a shear stress, which is parallel to the axis of the fiber in the jacket due to the mismatch of elasticity between the fiber and the jacket. The shear stress decreases gradually along the radial axle until it ends at the interface between the fiber and the jacket. The shear stress transmits from the jacket to the fiber. Due to the jacket in the tight-buffered fiber, the external load on the optical fiber depends on the transmission of the shear stress from jacket to the fiber core [11]. On the other hand, the data collected by BOTDR reflects the strain value of the glass fiber. Since both the Type A and B have outside coatings, the difference in coatings resulted in different strain values even with the same load, which is attributed to the mechanical property of the jacket. Most communication fibers used TPEE as jacket. TPEE is a macromolecular polymer, which has rubber-like elasticity and thermoplastic -like workability [12]. The jacket made of TPEE experiences creep deformation under constant stress, and the constant deformation gives rise to stress relaxation. Under the constraint of the cohesive force between the jacket and the coating, the jacket

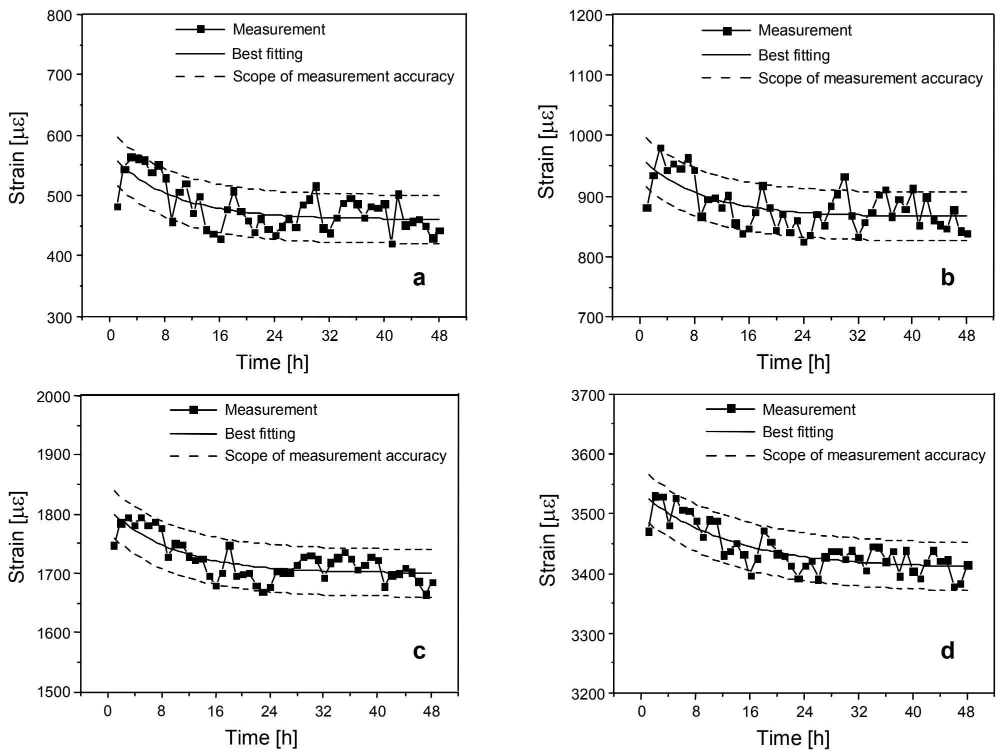

Fig. 9. Strain value of the Type-A changed with time under constant length stretching, $500\mu\varepsilon$ (**a**), $1000\mu\varepsilon$ (**b**), $2000\mu\varepsilon$ (**c**) and $4000\mu\varepsilon$ (**d**), within 48 hours

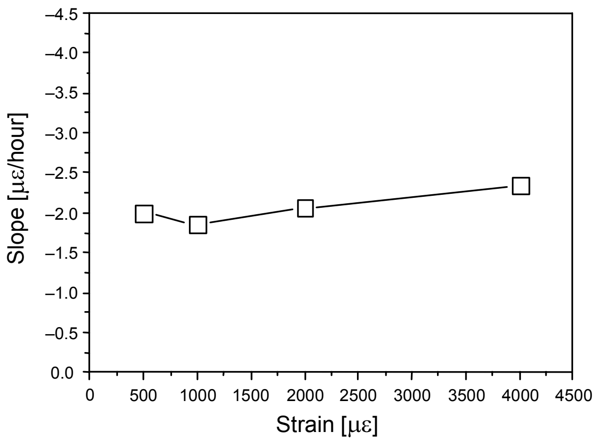

Fig. 10. Slope of the curves in the experiment for constant length stretching within 48 hours.

cannot deform freely. This produces a counteraction on the glass fiber. Therefore, tight-buffered fiber shows a special effect that is different from ordinary optical fiber under the constant load or length stretching.

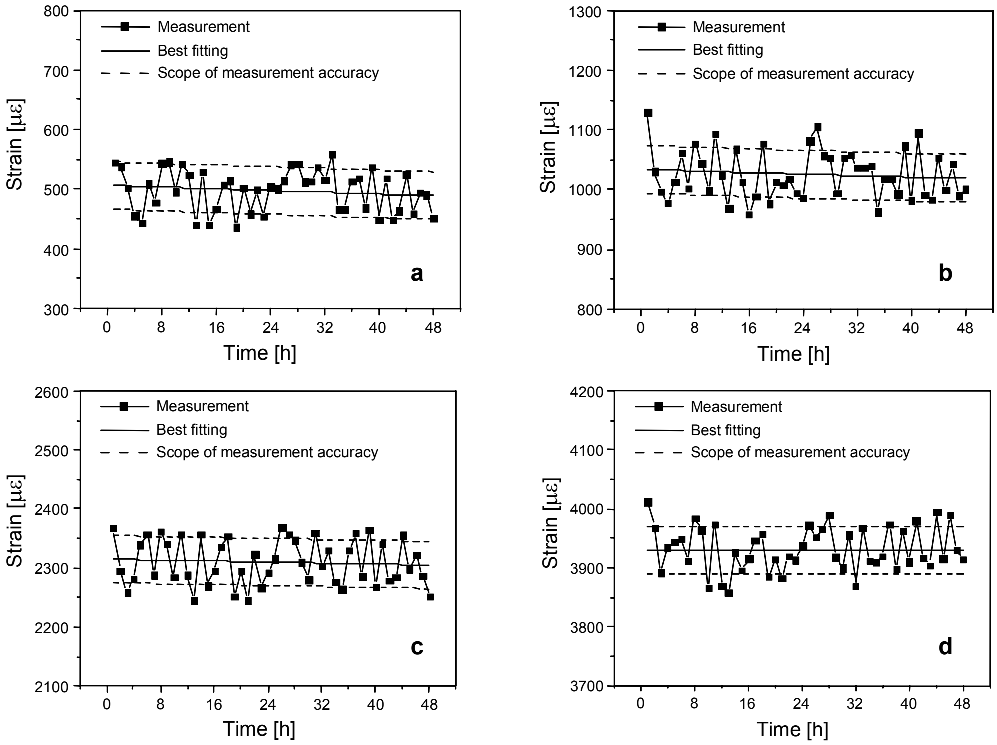

Fig. 11. Strain value of the Type-B changed with time under constant length stretching, $500\mu\varepsilon$ (**a**), $1000\mu\varepsilon$ (**b**), $2000\mu\varepsilon$ (**c**) and $4000\mu\varepsilon$ (**d**), within 48 hours.

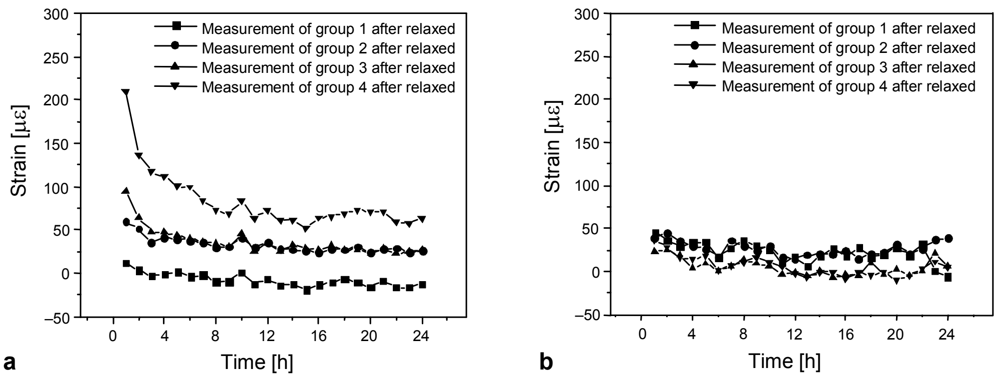

Fig. 12. Strain values of the Type-A (**a**) and Type-B (**b**) changed with time within 24 hours after being relaxed from constant length stretching.

3.1. Constant load stretching

For the Type-A under constant load stretching, external load was transferred to the glass fiber via jacket. In the course of being stretched, creep deformation occurred in jacket due to the shear stress. The deformation of jacket resulted in decreasing axial strength and tendency towards elongation. However, limited by the cohesive force at the interface between the jacket and the coating, the jacket could not elongate freely. Hence the jacket transferred more stress onto the coating. The external load drove the glass fiber to stretch accordingly, and then it would act on the glass fiber and the coating.

During 48 hours loading the creep deformation occurred, reversible high elastic deformation and irreversible viscous rheologic deformation occurred in the jacket [13]. When the external load was removed, the jacket did not recover quickly, and at the same time the cohesive force hindered the recovery of elasticity of the glass fiber. The reversible high elastic deformation disappeared over time, and the recovery of elasticity of the glass fiber, in turn, drove the jacket to contract. Therefore, after the unloading of the stress, the tight-buffered fiber shows a jacket effect: the strain decreases gradually to zero with the time.

3.2. Constant length stretching

During the constant length stretching, the strain of the optical fiber was constrained by the distance between the two fixed points. As long as the distance between the two fixed points was constant, the strain of the optical fiber would remain constant. But under long-time constant length stretching, stress relaxation occurred in the jacket. Although the external layer of the jacket remained stable, the inner layer of the jacket was shortened by $2\times L$ under the contraction force of the glass fiber (see Fig. 13). The degree of contraction ($2\times L$) was very weak considering the distribution the length (*i.e.*, 1.5 m); the fiber strain decreased only a little.

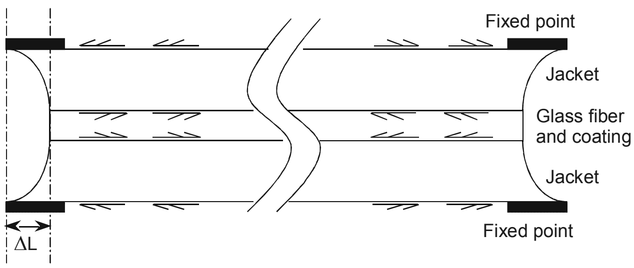

Fig. 13. Strain relaxation of jacket.

In addition, epoxy resin deformation at the fixed points and the delamination between the optical fiber and the epoxy resin are also the possible reasons for the jacket effect [14]. As a result, the strain value of the Type-B also decreased a little. After naving been relaxed from constant length stretching, the Type-A cannot recover from the stretch and it shows the tendency of decreasing to zero over the time. This unloading relaxation of the optical fiber is similar to that under constant load stretching.

4. Conclusions

The jacket effects to the stretched fiber have been studied over 48 hours stretching and 24 hours relaxation process. The previous study supports the conclusion as follows:

– the jacket has effect on the fiber strain in the long term of 48 hours;

– the creep deformation and stress relaxation of jacket is the leading cause of this jacket effect;

– to avoid the jacket effect on fiber strain, the jacket of tight-buffered fiber should be made of a new elastic material with good performance of creep deformation.

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