Long-Term Monitoring of White Rhino, Building with Tensegrity Skeletons

Ken'ichi KAWAGUCHI
Professor
Institute of Industrial Science, The University of Tokyo
Tokyo, JAPAN
kawaken@iis.u-tokyo.ac.jp

Shunji OHYA
Technical Researcher
Institute of Industrial Science, The University of Tokyo
Tokyo, JAPAN
ohya@iis.u-tokyo.ac.jp

Sammy VORMUS
Graduate Student,
National Superior School of Architecture of Paris La Villette, France
sammy.vormus@gmail.com

Summary

A pair of tensegrity skeletons, supporting a membrane roof, has been constructed at Chiba, Japan in 2001. Since their construction, the strain level of all struts and tendons of the skeletons have been continuously monitored and recorded. In this paper the long-term observation data of one of the tensegrity skeletons is reported and briefly discussed.

Keywords: *Tensegirty, monitoring, prestress, thermal change, membrane structure, tension structure.*

1. Introduction

White Rhino, a building covered with membrane roofs supported by two tensegrity skeletons, has been constructed at Chiba in Japan in June, 2001. The building is constructed in the University of Tokyo's experimental centre and houses different laboratories of the university. The name, White Rhino, comes from the exterior appearance of the roofs, the white colour and two "horns", where the membrane roofs are pushed up from inside by two isolated posts supported by tensegrity skeletons. These isolated struts absorb large deformation of membrane roof and transmits the force from membrane roof to the tensegrity frame. One of the two tensegrity frames is about ten meters high while the other is seven meters high.

Fig. 1: The tensegrity skeletons

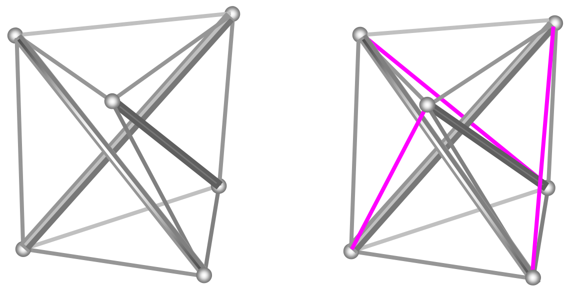
All struts and tendons of the two skeletons were equipped with a pair of strain gages, which were used for the real time monitoring during the construction of the W.R. Since we noticed that it was one of the earliest application of typical tensegrity frames to building structures we decided to continue to monitor the prestress states of the frame even after the construction. Then we added thermal couples to the monitoring system, to monitor the thermal variations, and have been recording the readings of the sensors every ten minutes, constantly, for almost ten years.

2. Overview of the White Rhino's skeleton

Either of the skeletons of the W.R. is a variation of so-called "Simplex" tensegrity. Simplex is considered as one of the most typical and simplest tensegrity frame, forming a twisted triangular prism, having nine tendons and three compression-struts (fig.2(a)). It is well known that Simplex has one infinitesimal inextensional displacement mode, a twisting motion between the upper and lower triangles, in which the frame exhibits extremely low rigidity.

For W.R. skeleton we added three more tendons between unconnected six points of Simplex (fig.2(b)). Although these additional three thin members does not change the peculiar appearance of the tensegrity much it improves the structural rigidity of the frame drastically. The rigidity of the frame becomes as high as that of a truss structure before the one of the tendons loose their prestress (fig.3). In fact, under vertical loads, the additional three tendons act as compression members as long as they are in tension with the existence of initial prestress [1].

One more different point in the geometry of the W.R. skeleton from Simplex is that its general shape is rather trapezoidal than prismatic. In order to fit the "horn" configuration of the membrane roof we designed the upper triangle smaller than the bottom triangle. In order to support the membrane roofs, each frame has an extra set of three suspension tendons supporting an isolated post member that is pushing up the membrane roof and transmitting the external loads on the roof to the tensegrity frame (fig.4). At the lower end of the isolated post it is connected to the suspended tendons with a connection where the post can rotate in a certain range so that it can accommodate the large deformation of the membrane roof. Two tensegirty skeleton have different heights each other. One is ten-meter high and it is called



(a) *Simplex* (b) *Addition of three tendons*

Fig. 2: Concept of White Rhino's skeleton

frame A, while the other is about seven-meter high, called frame B.

Adding members generally makes a frame more “redundant” and complicated. In the case of W.R. skeleton the addition of three tendons eliminates the inextensional displacement mode, as previously described, and makes the skeleton very rigid. However, on the other hand, the addition increases the number of independent prestress mode of the skeleton to three, which is just one for the original Simplex, and this made the control of prestress during the construction more complicated and it required careful investigations for the prestressing process of the skeletons. Therefore we conducted a mock up test and checked our scheme for prestressing and decided to apply the real time monitoring of the members’ strain during the real construction at the site. We also decided to apply manual process for the introduction of prestress, although the construction company proposed to use hydraulic jacks, because we thought the manual process was more suitable than to use mechanical devices in this case (fig.5), considering controllability and required prestress level.

A pair of strain gages was attached to every member of the skeletons and initialised before the construction during when the members were horizontally and freely laid on the ground in their natural lengths. Each pair of strain gages was attached in a way that the deformation due to temperature change was cancelled off and the reading gave pure strain due to the axial force. The main concern of the monitoring was to know the real behavior of the full-scale tensegrity frames under thermal variation. The room temperature at 1m high from the floor level is also recorded. A thermocouple is attached to the foot of one of the main struts of each tensegrity frame and records temperature of it directly. This temperature data is thought to represent the temperature of the skeleton itself. All these monitored readings have been recorded every ten minutes, constantly, since the completion of the building, for about ten years.

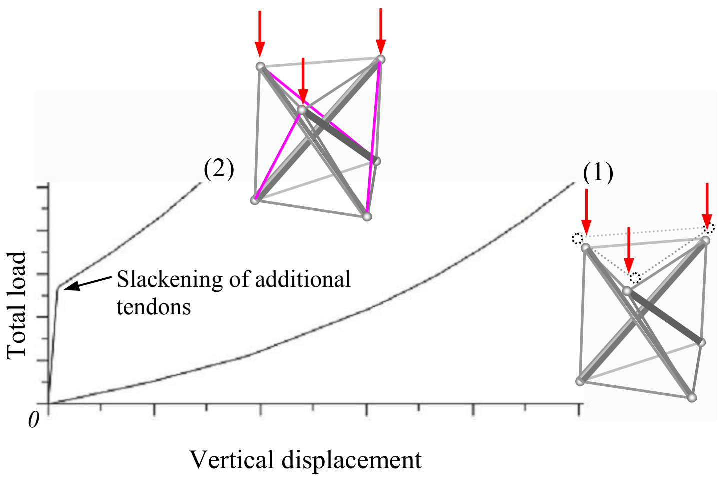


Figure 3: Typical load-displacement relationship in vertical direction of a top joint for the Simplex (1) and the W. R. Skeleton (2)

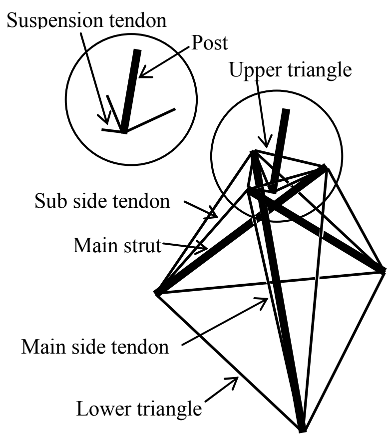


Figure 4: Schematic view of the frame

3. Long-term observation data of the frame A

Because of the limited space of this report data of only frame A is indicated here. Locations of the sensors are indicated in fig.8. Changes of axial force calculated from recorded strain gage data, by multiplying Young's modulus and cross sectional area of each member, are plotted in the figs.9-15.

(a) Mock-up Test

(b) Manual prestressing process

Figure 5: The mock-up test before the construction and manual prestressing tested for the mock-up.

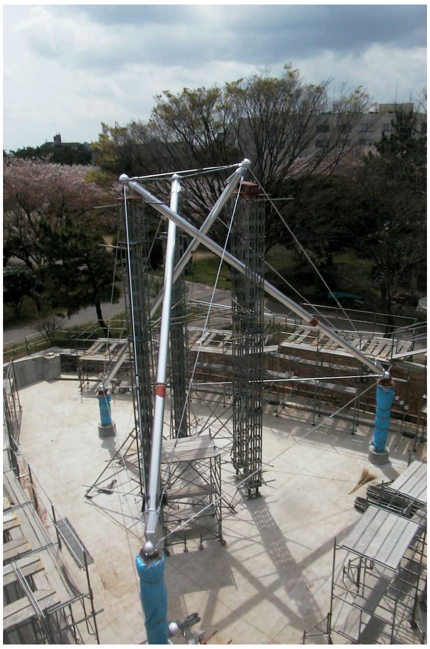


Figure 6. Frame A under construction

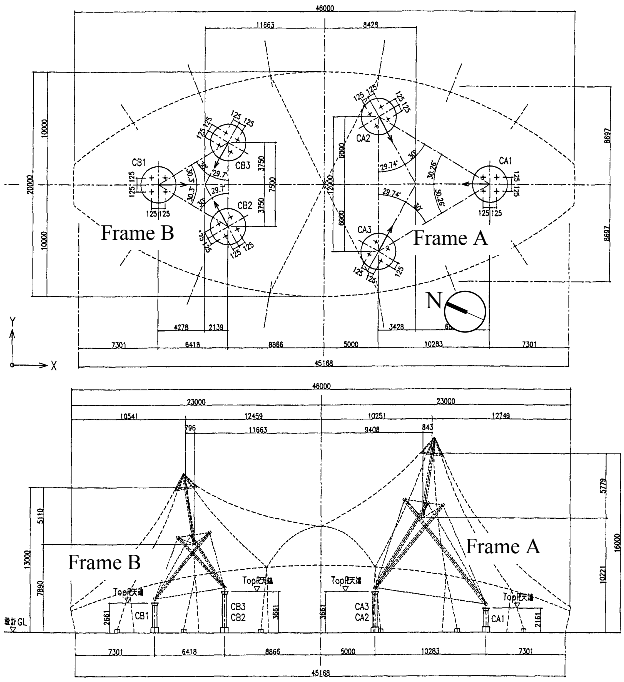


Figure 7: Plan and section view of the building

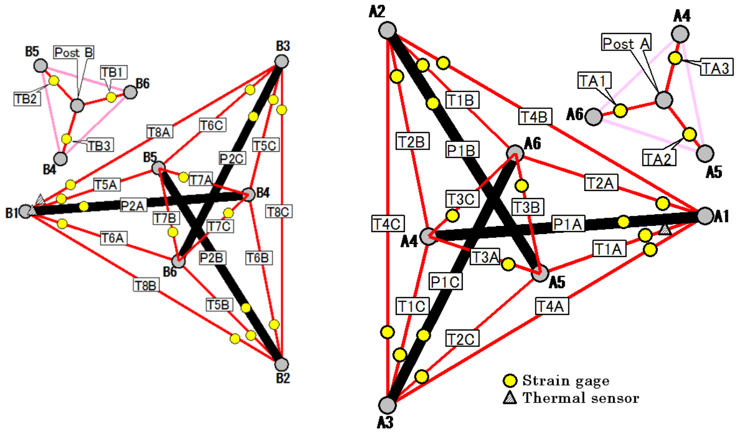


Figure 8: Locations of strain gages and thermosensors on the frames

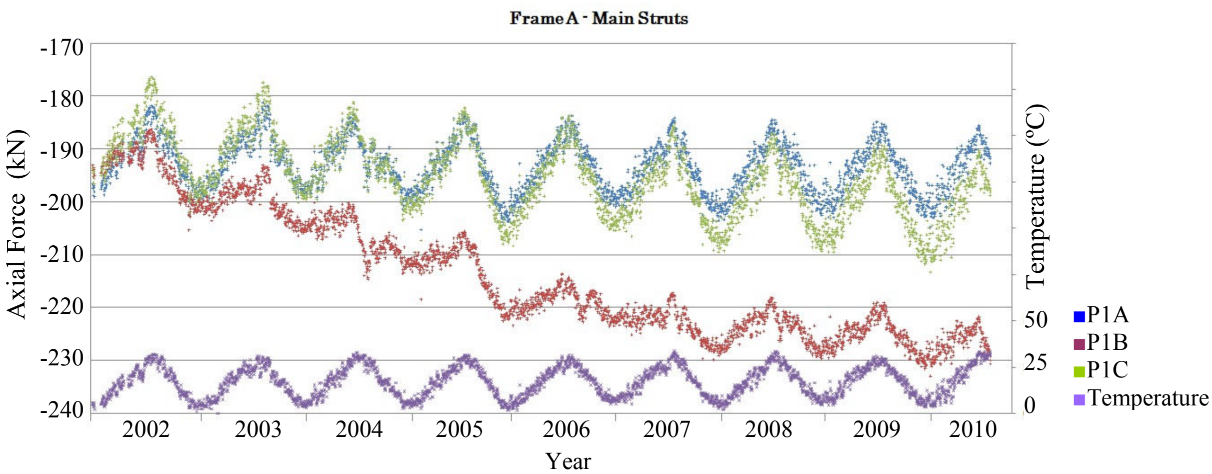


Figure 9: Long-term observation of axial force change in the Main struts (Frame A)

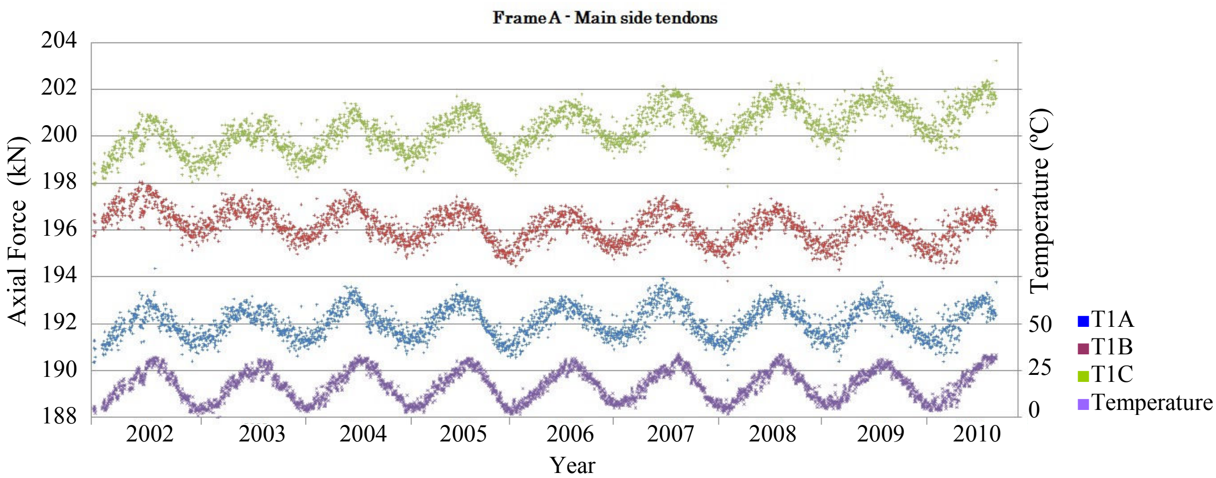


Figure 10: Long-term observation of axial force change in the Main side tendons (Frame A)

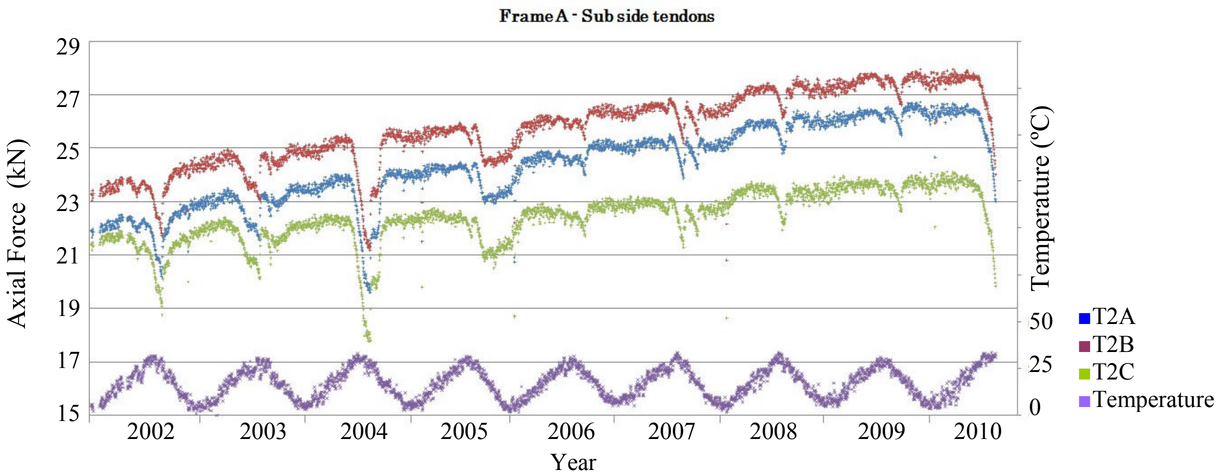


Figure 11: Long-term observation of axial force change in the sub-side tendons (Frame A)

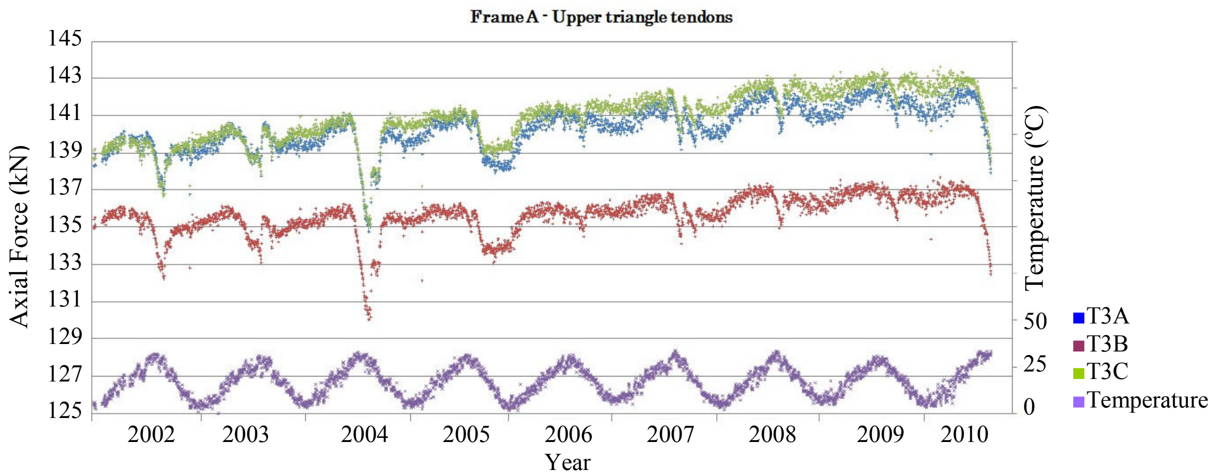


Figure 12: Long-term observation of axial force change in the upper-triangle tendon (Frame A)

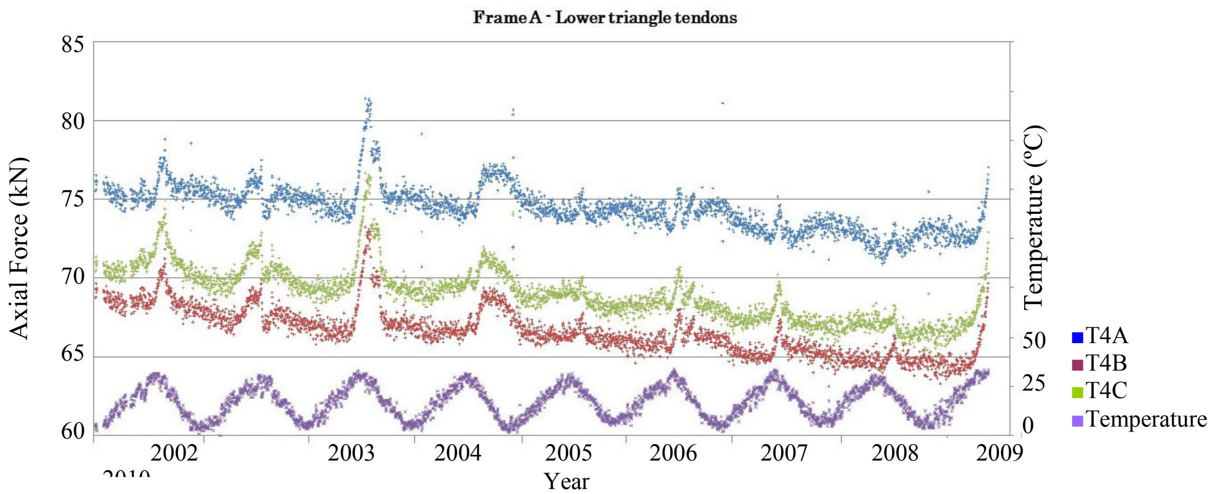


Figure 13: Long-term observation of axial force change in the lower-triangle tendon (Frame A)

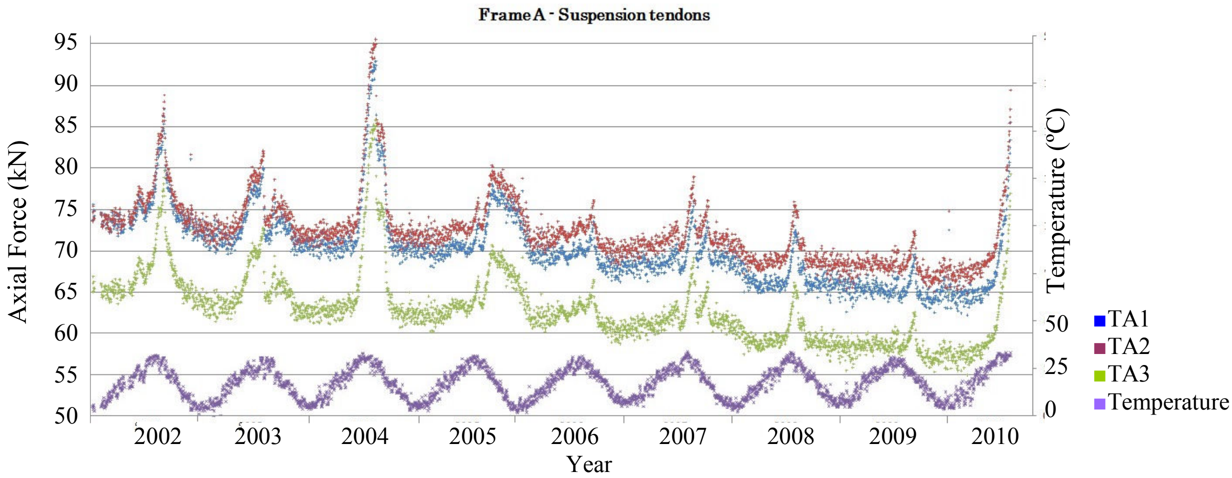


Figure 14: Long-term observation of axial force change in the suspension tendons (Frame A)

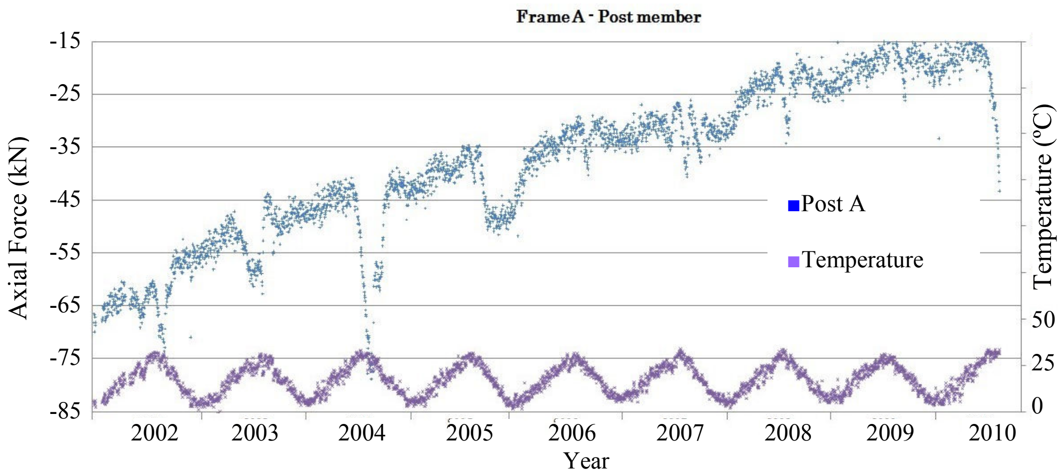


Figure 15: Long-term observation of axial force change in the post (Frame A)

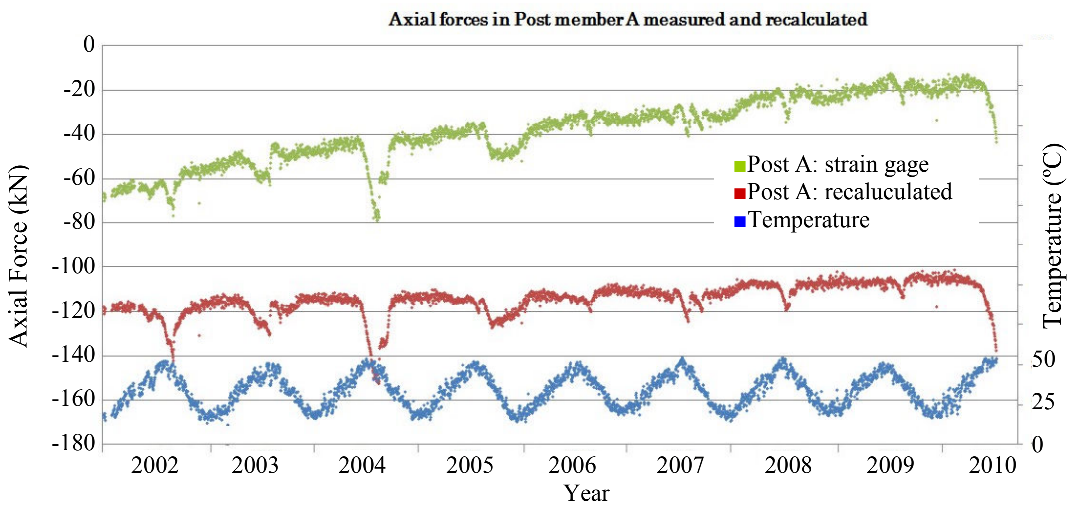


Figure 16: recalculated axial force change in the post (Frame A)

4. Discussions

The axial forces in main struts and main side tendons directly follow the temperature change (figs.9 and 10) and it seems the effect of other factors are very minor. On the other hand the axial forces in other members does not follow the temperature change directly and it seems other factors influence them, although they naturally have a certain yearly regularity. The variation ranges of mean axial force are indicated in table.1. Each part has its typical variation-range. In the percentage expression it can be seen that the variation-ranges of the members of original Simplex are rather modest while those of the additional members, sub side tendon and suspension tendons, are comparatively large. At a glance it is obvious that the behaviour of P1B and Post A are considerably dropping from reasonable range. So far the reasons of these are not detected yet however it seems there are some malfunctions in the strain gage systems of these members. Since the behaviours of P1A and P1C are similar we may assume that P1B behaves like others. For post A we can recalculate its axial force based on the readings of TA1, TA2 and TA3 since they should be in the pure equilibrium with the post A at the supporting point. This recalculated axial force is plotted in fig. 16.

Table 1: Variation-range of mean axial force in Frame A

		Variation-range of mean axial force(kN)
Main struts	P1A	-2.4 (-1.30%)
	P1B	-31.4 (-16.80%)
	P1C	-11.0 (-6.20%)
Main side tendons	T1A	0.2 (0.10%)
	T1B	-1.2 (-0.60%)
	T1C	0.4 (0.20%)
Sub side tendons	T2A	4.0 (18.20%)
	T2B	4.1 (17.70%)
	T2C	2.0 (9.30%)
Upper triangle tendons	T3A	2.0 (1.40%)
	T3B	1.0 (0.70%)
	T3C	3.5 (2.50%)
Lower triangle tendons	T4A	-2.7 (-3.60%)
	T4B	-4.0 (-5.80%)
	T4C	-2.9 (-4.10%)
Suspension tendons	TA1	-8.0 (-10.90%)
	TA2	-4.6 (-6.30%)
	TA3	-7.0 (-10.80%)
Post member	Post A	44.7 (67.70%)

Every reasonably recorded value shows slight but steady change in the long-term view. For example main struts, P1A and P1C have been slightly loosing their compression forces. The recalculated axial force of post A in fig.16 indicates slight reduction of its compression force in ten years. From the previous discussions these long-term change may be due to the relaxation of membrane roof [2]. Further discussions are needed for more detailed observations.

5. References

[1] KAWAGUCHI K. and LU Z-Y, “Construction of three-strut tension systems”, Proceedings of 5th International Conference on Space Structures, edt. by G. Parke & P. Disney, Vol.1, 2002, 8, pp.1-10.

[2] KAWAGUCHI K. and OHYA S., “Monitoring of full-scale tensegrity skeletons under temperature change”, Proceedings of IASS Symposium 2009, Valencia, edt. by A.Domingo and C.Lazaro, 2009, PAP128, 8pages.