Manufacture Errors Analysis and Control of Cable Dome

Jianhua Zhang[1,*], Ke Sun[2] and Zhenqing Wang[1]

[1]*College of Aerospace and Civil Engineering, Harbin Engineering University, Harbin, 150001, China*

[2]*College of Shipbuilding Engineering, Harbin Engineering University, Harbin, 150001, China*

Abstract: Applying prestress is the key technique of the cable dome. However, it is difficult to ensure that designed prestress of cables have been exactly applied to the structure in the site due to the fact that various kinds of errors will be introduced during construction. Thus it is necessary to present an effective method to guide construction to avoid construction team regulate the real prestress of cables repeatedly. In the paper, sensitivity analysis method based on spearman rank-order correlation is presented and the random errors are simulated by Monte Carlo method to solve the manufacture error. The sensitivity of effect of bearing and cable length manufacture errors on structural performance is analyzed in a numerical model of cable dome with the diameter of 62m. A cable dome model with diameter of 6m is designed and experimented. The experiential results are mostly consistent with the theoretical ones, which prove that the analysis theory is correct and the control method is effective. At last, some suggestions are made for manufacture errors of cable dome.

Keywords: Cable dome, sensitivity analysis, spearman rank-order correlation, manufacture errors.

1. INTRODUCTION

Cable dome, proposed by Geiger after extending Fuller's ideas of tensegrity [1, 2], is a kind of prestressed space structure. Cable dome system composed of continuous prestressed cables and individual compression struts is a self-equilibrium system. The successful applications of cable dome in designing in the circular roof structures of the Gymnastics Arena (diameter 119.8 m) and the Fencing Arena (diameter 89.9 m) constructed for Seoul Olympics in 1988 [3]. From then, several projects have been built in the world such as the Suncoast Dome (circular plan, diameter 210 m) built in St. Petersburg, the Red bird Arena with the first elliptical plan (diameter of the long axis is 91.4 and short axis is 76.8m), which was built in Illinois State University. Georgia Dome [4] (elliptical plan, diameter of the long axis and short axis is 240.79and 192.02 m respectively) was designed for the Atlanta Olympic Games in 1996. As an innovative, light structure system, cable dome attracts a lot of attention from engineers and wildly used in large span structures.

Cable dome is different from other traditional structures that its stiffness comes from introduced prestress during construction other than obtains from the geometry and material. The stiffness and shape of the cable dome structure is correlative with the prestress distribution induced. Therefore, it is the key issue to control the force of cables and induce designed value of prestress to the structure accurately. In practical constructions, however, it is difficult to ensure no difference between the real prestress distribution and the designed value due to existed construction errors. The mechanical problems which considering the prestressing of tendons in turn encountered during the construction had been solved theoretically [5-8]. In fact, there is still a great difference between the real prestress and the designed value due to existing construction errors. Therefore, it is necessary to study how to control construction errors effectively.

The objective of this paper is to study the sensitivity of bars regulated on structural behaviors to determine the feasible bar to improve construction efficiency and maximum allowable manufacture errors. The basic sensitivity analysis theory is firstly presented in details, then sensitivity of manufacture errors in different cases on structural behaviors is analyzed and maximum allowable errors limits are presented. In the following, an experimental modal is designed and tested. At last, some suggestions on construction errors are given out, which provide a reference for cable dome design and construction.

2. SENSITIVITY ANALYSIS METHOD BASED ON SPEARMAN RANK-ORDER CORRELATION

Spearman rank-order correlation method is used to test non-parametric statistical correlation [9]. A sample $x_1, x_2, ..., x_n$, the sample elements are arranged in ascending order $x_{(1)}, x_{(2)}, ..., x_{(n)}$, if $x_i = x_{(R_i)}$, that is, the rank of x_i (i = 1,2 , ..., n) is R_i , (R_i = 1,2, ..., n) in the sample $x_1, x_2, ..., x_n$. It can be seen from the definition of rank, the rank R_i is the order of the entire sample sequence from small to large.

For the data $\begin{pmatrix} x_1 \\ y_1 \end{pmatrix}, \begin{pmatrix} x_2 \\ y_2 \end{pmatrix} \cdots \begin{pmatrix} x_n \\ y_n \end{pmatrix}$, the Spearman rank correlation coefficient is calculated as follows: the rank of

*Address correspondece to this author at the College of Aerospace and Civil Engineering, Harbin Engineering University, Harbin, 150001, China;
Tel: +86-451-82519201; Fax: +86-451-82519210;
E-mails: jhzhang1980@hotmail.com, zjh@hrbeu.edu.cn

x_i in x_1, x_2, ..., x_n is R_i, and the rank y_i in y_1, y_2, ..., y_n is Q_i (i = 1,2, ..., n). Construct a new data with R_i and Q_i instead of x_i and y_i respectively, the Spearman rank correlation coefficient of the original data is

$$r_s = \frac{\sum_{i=1}^{n}(R_i - \overline{R})(Q_i - \overline{Q})}{\sqrt{\sum_{i=1}^{n}(R_i - \overline{R})^2}\sqrt{\sum_{i=1}^{n}(Q_i - \overline{Q})^2}} \quad (1)$$

Where, $\overline{R} = \frac{\sum_{i=1}^{n} R_i}{n} = \frac{n+1}{2}$, $\overline{Q} = \frac{\sum_{i=1}^{n} Q_i}{n} = \frac{n+1}{2}$. The rank correlation coefficient range from-1 to1, when two variables monotonically increase, the correlation coefficient is positive (+1.0 means perfect positive correlation); when two variables monotonically decrease, the correlation coefficient is negative (-1.0 means perfect negative correlation); when there is no relationship between the two variables, the relevant coefficient is zero. The greater is absolute value, the greater is the correlation between two variables.

In the sensitivity analysis, structural response is named y, and construction errors named x. Construction errors are simulated by Monte Carlo method. r_s denotes correlation between structural responses to parameters. Sensitivity of construction errors to structural performance is the correlation coefficient between errors parameters and structural behaviors. Therefore, the sensitivity analysis can be carried out by judging the correlation of construction errors. If the error parameter is highly correlative with the structural performance, the effect is significant. Therefore, the parameter should be controlled strictly in the practical construction.

3. SENSITIVITY ANALYSIS OF MANUFACTURE ERRORS

Errors generated in construction process are random. Generally, manufacture errors should conform to normal distribution [10]. Cables length and bearing manufacture errors are assumed to subject to normal distribution. Sample size is 2000, R_a denotes allowable manufacture errors and δ denotes manufacture control accuracy, according to actual construction, δ takes 5%. The actual manufacture error range R_e is

$$R_e = [(1-\delta)R_a, (1+\delta)R_a] \quad (2)$$

Structural Model

The structural model employed is shown in Figs. (**1-3**), it is noticed from Fig. (**1**) that the network use the quadrangled geometry. The numbers of supports are shown in Fig. (**2**). Fig. (**3**) displays the layout and dimension of the cable dome, the span and the rise of the dome are 62m and 9.3 m respectively. In Fig. (**3**), letter RC1, RC2 and RC3 denote the

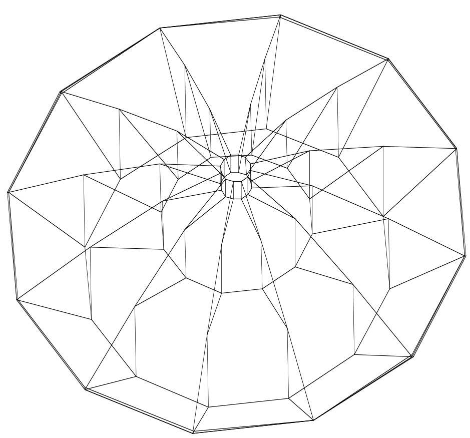

Fig. (1). Perspective of cable dome.

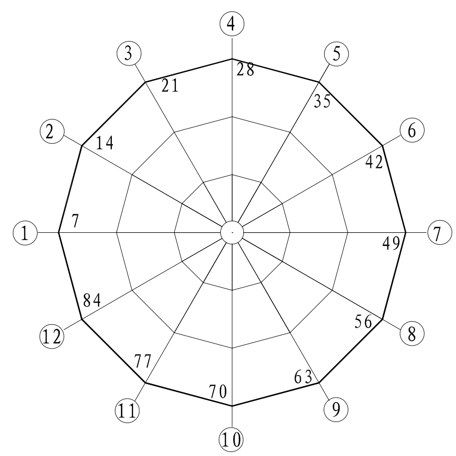

Fig. (2). Bearing number of cable dome.

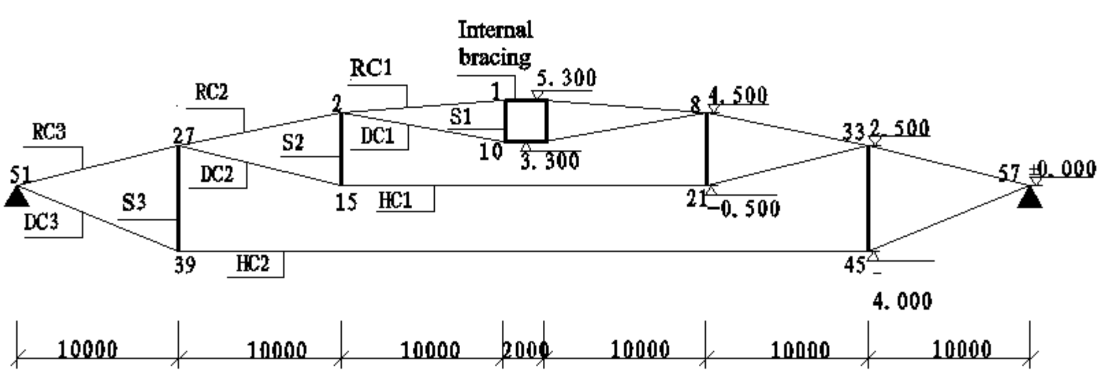

Fig. (3). Section of axis 1-7.

ridge cable from outer layer to inner layer; DC1, DC2 and DC3 denote the diagonal cable, HC1 and HC2 denote the hoop cable, while S1, S2 and S3 denote the compression strut. The initial presstress distribution and cross section area are given in Table **1**.

Sensitivity Analysis of Bearing Manufacture Errors

Bearing manufacture errors *Rx*, *Ry* and *Rz* in radial, tangential and vertical direction respectively are taken as the input variables, and internal force of elements and nodal displacements in the axis 1-7 are taken as output variables.

In practical engineering, manufacture errors in all direction may produce in all bearing. Referring to "*Technical Specification for Latticed Shells*" (Section 6.7) [11], 7 cases (shown in Table **2**) are considered including different random manufacture errors in different direction. Change ratio of internal force and nodal displacement are shown in Tables **3** and **4**.

Table1. Initial Prestress Distribution and Cross Section Areas of Elements for Cable Dome

	RC1	RC2	RC3	DC1	DC2	DC3
Initial prestress（kN）	155.23	256.35	428.07	97.51	178.63	287.99
Area (mm^2)	731	731	1193	269	500	731
	HC1	HC2	S1	S2	S3	
Initial prestress（kN）	329.99	516.68	-11.61	-51.35	-106.98	
Area (mm^2)	731	1424	829.4	2120.6	2748.9	

Table 2. Cases of Bearing Manufacture Errors Considered

Case	Mean of *Rx* (mm)	Mean of *Ry* (mm)	Mean of *Rz* (mm)	δ
1	10	10	10	5%
2	20	20	20	5%
3	30	30	30	5%
4	20	10	10	5%
5	10	20	10	5%
6	10	10	20	5%
7	10	20	30	5%

Table 3. Change Ratio of Internal Force in 7 Cases of Manufacture Errors (%)

	Case1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
RC1	7.95	8.26	10.25	8.31	4.27	7.90	11.64
DC1	0.54	0.95	0.45	1.02	0.02	0.73	0.31
RC2	5.24	5.34	6.33	5.40	2.57	5.04	7.10
DC 2	-0.67	-0.27	-0.48	-0.22	-1.39	-0.50	-0.61
RC 3	2.79	3.03	3.51	3.08	0.93	2.74	3.91
DC 3	-3.36	-2.96	-3.14	-2.91	-4.04	-3.20	-3.30
HC1	-0.66	-0.24	-0.51	-0.20	-1.28	-0.46	-0.71
HC2	-3.34	-2.93	-3.20	-2.89	-3.96	-3.15	-3.40
S1	3.49	3.90	4.55	3.82	2.09	3.72	4.35
S2	1.12	1.35	1.56	1.44	-0.50	1.06	1.97
S3	-1.47	-1.12	-1.24	-1.07	-2.41	-1.35	-1.25

It can be seen from the Table **3**, the effect of manufacture errors on internal force of RC1 is most significant and then is the effect on RC2, 3 and DC3, but the effect on HC1, DC 1 and DC 2 is not significant. Compared with case 1 and 4, the effect on internal force increase with the increase of *Rx*, Compared with case 1 and 5, the effect on internal force decrease with the increase of *Ry*. From case 1 and 6, it can be seen that the effect on internal force is not significant with the increase of *Rz*. The nodal displacement increases with the increase of manufacture errors as shown in Table **4**.

In summary, the effects are not great on structural performance of bearing manufacture errors. Maximum change ratio of internal force is 11.6% and maximum nodal displacement is 29.49mm(less than 1/2000 of span) when *Rx*, *Ry*, *Rz* take the value in Case 7. The effect of radial manufacture error *Rx* is most apparent. Therefore, the radial manufacture errors should be controlled strictly. It is advised to control within 1/2000 of distance between adjacent supports for the span within 60m.

Sensitivity Analysis of Cable Length Manufacture Errors

5 cases are considered including different random cable length manufacture errors. Mean of maximum cable length manufacture error are 0.05%, 0.10%, 0.15%, 0.20% and 0.25% of cable length respectively in case1 to 5, δ is 5%. Change ratio of internal force and nodal displacement are shown in the Table **5**.

From Table **5**, the effect of cable length manufacture errors on structural performance are significant. Take case 1 as an example, if the maximum cable manufactures error is 0.05% of cable length, the internal force of RC 1 will change 36%. Therefore, cable length manufacture should be controlled strictly. However, it is not appropriate or economical that manufacture errors of every cable are limited to the same value in practical construction, so it is necessary to carry out sensitivity analysis of manufacture errors for cable length in various positions on structural behaviors. The numerical results are shown in Figs. (**4-7**).

It can be seen that the sensitivity of manufacture errors in HC2 to internal force are most significant, that is from 45% to 67%, followed by RC3, DC3 and HC1.While sensitivity of manufacture errors RC1 and DC1 and struts are not significant. Therefore, manufacture errors in HC2, RC3, DC3 and HC1 should be strictly controlled in practical engineering. For a cable with length of 10 to 30m, the maximum errors of HC2, RC3, DC3 and HC1 are advised to control to 0.05% of cable length, RC2 and DC2 are controlled to 0.10%, and RC1 and DC1 controlled to 0.15% referring to domestic cable manufacture industry specifications.

4. SUGGESTIONS ON CONSTRUCTION

In practical construction, there are manufactures errors in bearing and bars, which may bring great deviation between

Table 4. Nodal Displacement in Construction Errors of 7 Cases(mm)

Node	Case1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
1	7.95	8.26	10.25	8.31	4.27	7.90	11.64
2	0.54	0.95	0.45	1.02	0.02	0.73	0.31
27	5.24	5.34	6.33	5.40	2.57	5.04	7.10

Table 5. Change Ratio of Internal Force in 5 Cases of Cable Length Manufacture Errors (%)

	Case1	Case 2	Case 3	Case 4	Case 5
RC1	36.33	62.63	89.07	123.73	150.51
DC1	24.16	47.26	69.22	95.59	115.26
RC2	31.47	56.49	81.14	112.47	136.40
DC 2	23.76	46.71	69.19	96.46	119.36
RC 3	28.28	52.44	76.19	105.82	129.34
DC 3	20.60	43.13	65.16	92.89	115.39
HC1	23.77	46.73	69.21	96.48	119.39
HC2	20.61	43.14	65.17	92.89	115.41
S1	28.82	53.12	76.75	106.10	128.26
S2	26.09	49.72	72.92	101.59	124.78
S3	22.94	45.97	68.54	96.82	119.58

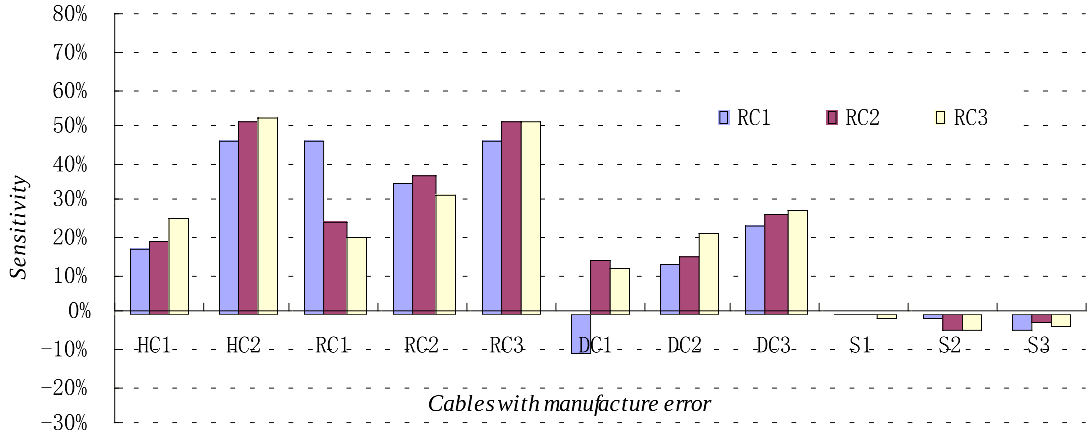

Fig. (4). Sensitivity of cable length manufacture errors to internal force of ridge cable.

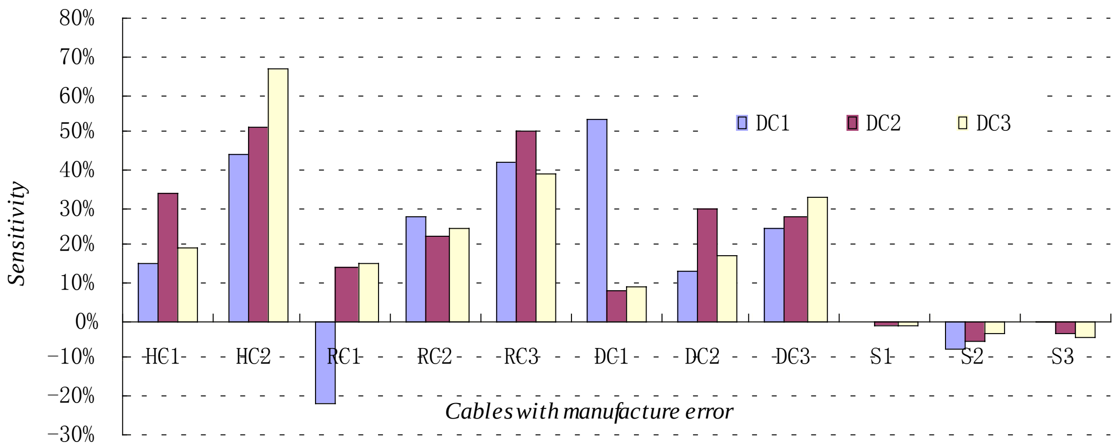

Fig. (5). Sensitivity of cable length manufacture errors to internal force of diagonal cables.

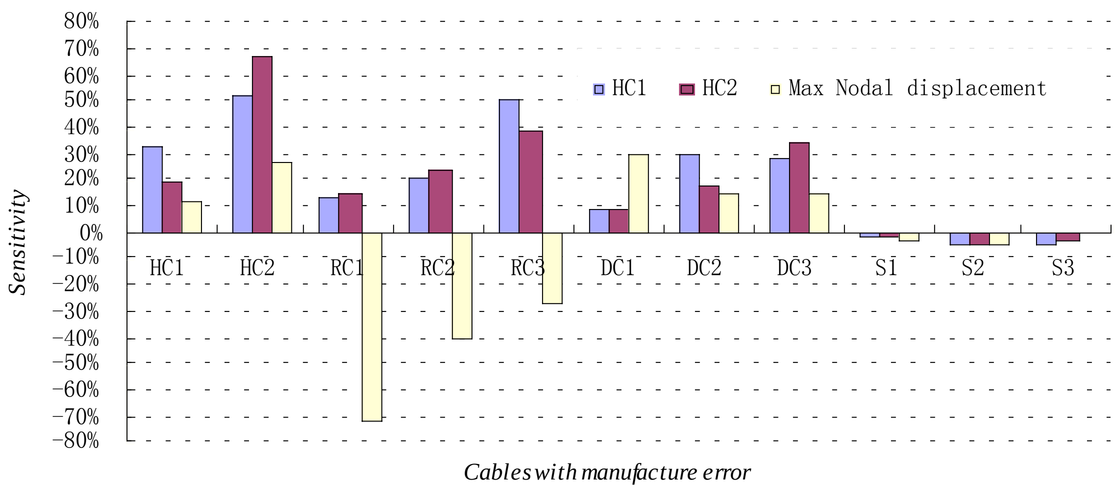

Fig. (6). Sensitivity of cable length manufacture errors to internal force of hoop cables and maximum nodal displacement.

actual internal force and design values after forming. Therefore, it needs a clear guideline to regulate errors effectively.

From the construction errors analysis in above section, we know that components with significant sensitivity have apparent effect on internal force and therefore should be controlled strictly. To the extent, if those components could be regulated, the construction efficiency would be improved. In theory, adjusting the bearing position can eliminate errors, but the actual location of bearings is generally fixed. It is not feasible to regulate bearing positions, but it is to regulate bars length in practical engineering.

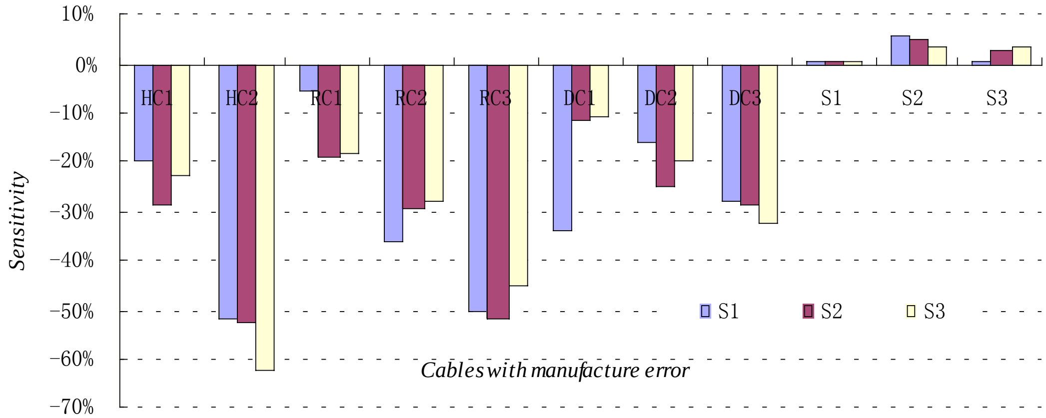

Fig. (7). Sensitivity of cable length manufacture errors to internal force of struts.

The paper present regulated bars in priority sequences, as shown in Table **6**, the symbol (-) indicates that the force of regulated bars monotonically decrease with the member forces of the first row in table. For example, in practical construction, it is found that the internal force of RC1 is smaller than the design value, so we could increase this value by increasing internal force of RC3, RC1, HC2, RC2, XC3, HC1, DC2 and decreasing internal force of DC1, S3, S2 and S1. However, the most effective way is to regulate RC3 length, that is to say, shortening the RC3 length can significantly increase the RC1 internal force. From the priority sequences, it is not effective to regulate S1 length, because lengthening the DC1 length will not be great to change magnitude of RC1 internal force.

Considering top four bars in Table **6** are the most sensitive to internal forces, it is suggested to regulate those bar length in accordance with the priorities listed in the control group in the practical construction, which can improve the accuracy and efficiency of construction.

5. EXPERIMENTS

An experimental model with diameter 6m (shown in Fig. **8**) have been carried out to test the theory. In the experiment, the cable length can be shortened or lengthened by regulating the device in Fig. (**9**). The bearing position can be regulated by the bolt in the ring beam shown in Fig. (**10**). Experimental results show that the bar internal force can

Fig. (8). Experimental model.

Table 6. Priority Sequence Table of Adjusted Member Bars

Sequence	RC1	RC2	RC3	DC1	DC2	DC3	HC1	HC2	S1	S2	S3
1	RC3	HC2	HC2	DC1	HC2	HC2	HC2	HC2	HC2 (-)	HC2 (-)	HC2 (-)
2	RC1	RC3	RC3	HC2	RC3	RC3	RC3	RC3	RC3 (-)	RC3 (-)	RC3 (-)
3	HC2	RC2	RC2	RC3	HC1	DC3	HC1	DC3	RC2 (-)	RC2 (-)	DC3 (-)
4	RC2	DC3	DC2	RC2	DC2	RC2	DC2	RC2	DC1 (-)	HC1 (-)	RC2 (-)
5	DC3	RC1	HC1	DC3	DC3	HC1	DC3	HC1	DC3 (-)	DC3 (-)	HC1 (-)
6	HC1	HC1	DC2	RC1 (-)	RC2	DC2	RC2	DC2	HC1 (-)	DC2 (-)	DC2 (-)
7	DC2	DC2	RC1	HC1	RC1	RC1	RC1	RC1	DC2 (-)	RC1 (-)	RC1 (-)
8	DC1 (-)	DC1	DC1	DC2	DC1	DC1	DC1	DC1	S2	DC1 (-)	DC1 (-)
9	S3 (-)	S2 (-)	S2 (-)	S2 (-)	S2 (-)	S2 (-)	S2 (-)	S2 (-)	RC1 (-)	S2	S3
10	S2 (-)	S3 (-)	S3 (-)	S3	S3 (-)	S3 (-)	S3 (-)	S3 (-)	S1	S3	S2
11	S1 (-)	S1 (-)	S1 (-)	S1 (-)	S1 (-)	S1 (-)	S1 (-)	S1 (-)	S3	S1	S1

approach to the design value after initial regulating in accordance with the priority sequence in the table. After regulating twice, the deviation between actual internal force and design value can be controlled within 10%.

Fig. (9). Connection used to regulate cable length.

Fig. (10). connection used to regulate bearing.

6. CONCLUSIONS

Manufacture errors analysis for cable dome are carried out using sensitivity analysis method based on spearman rank-order correlation. Numerical results demonstrate that the sensitivity effect of radial bearing manufacture error on structural performance is most significant and should be controlled strictly. It is advised to control within 1/2000 of distance between adjacent supports for the span within 60m. Numerical results show that manufacture errors in HC2, RC3, DC3 and HC1 should be strictly controlled. For a cable with length of 10 to 30m, the maximum errors of HC2, RC3, DC3 and HC1 are advised to control in 0.05% of cable length, RC2 and DC2 are controlled in 0.10%, and RC1 and DC1 in 0.15%.

Aimed at cables in different position, effective regulating sequences are presented. It is advised to regulate the top four bars in priority sequence. The experiment has tested high regulating efficiency in accordance with the priority sequence mentioned in this paper.

ACKNOWLEDGMENTS

This research is financially supported by the Fundamental Research Funds for the Central Universities (Grant No.HEUCF100208), Harbin Special Study Fund for technological innovation (Grant No.2009RFQXG073)

REFERENCES

[1] R. B. Fuller, *"Tensile-integrity structures"*, U. S. Patent 3063521, December 13, 1962.

[2] D. H. Geiger, *"Geiger roof structure"*, U. S. Patent 4736553, April 12, 1988.

[3] D. H. Geiger, "The design and construction of two cable domes for the Korean Olympics", In: *Proceedings of IASS-ASCE International Symposium on Shells, Membranes and Space Frames*, 1986, pp. 265-272.

[4] M. P. Levy, "The Georgia Dome and beyond achieving lightweight-long span structure", In: *Proceedings, IASS-ASCE International Symposium*, 1994, pp. 560-562.

[5] H. Deng and S.L. Dong, "Analytical method of pretensioned reticulated structure", *Journal of Zhejiang Univeristy*, vol. 32, pp.42-47, September 1998 (in Chinese).

[6] J.H. Zhang and Y.G. Zhang, "Construction process analysis of Cable Dome", *Journal of Wuhan University of Technology*, vol. 30, pp.91-94, April 2008 (in Chinese).

[7] Tang J.M. Tang and Z.Y. Shen, "The Research of computation method of construction process simulation for axial symmetric Cable Domes with circular plane", *China Civil Engineering Journal*, vol. 31, pp.24-32, October 1998 (in Chinese).

[8] X.F. Yuan, S.L. Dong, "Inverse analysis of construction process of cable dome", *Journal of Building Structures*, vol. 22, pp. 74-78. April 2001 (in Chinese).

[9] D.B. Yang, Y.G. Zhang and J.Z. Wu, "Sensitivity analysis based on ANSYS and its application to single layer reticulated shell". *World Earthquake Engineering*, vol. 25, pp. 87-91, December 2009 (in Chinese).

[10] L.M. Zhang, W.J. Chen and S.L. Dong, "Manufactures errors and its effects on the initial prestress of Geiger cable domes", In: *Proceeding of IASS- APCS*, 2006, pp.16-20.

[11] JGJ 61-2003, "*Technical Specification for Latticed Shells*": PRC industry standard, China Architecture & Building Press, 2003 (in Chinese).

Received: September 05, 2010 Revised: November 21, 2010 Accepted: December 03, 2010