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SIMULTANEOUS FORCE AND DEFORMATION CONTROL OF CABLE ARCH STAYED BRIDGES

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ABSTRACT

The tendency to build cable arch stayed bridges is increasing due to their aesthetic appearance and efficient performance. Due to overloading or time passing, they may face deformation thus they are required to be reshaped. For the same explanations the cables could undergo high tension and some others face slack, in order to keep the bridge safe in terms of stress failure, the redistribution of internal force of cables is essential. Pragmatically, the displacement restoring and the force redistribution are simultaneously necessary, since both issues arise together. This paper deals with simultaneous control of nodal displacement and internal force of cable theoretically by MATLAB Program and experimentally of a linear and a geometrically nonlinear model. The paper also shows that how the technique of adjustment response to control linear and geometrically nonlinear structures. It was determined that the technique was pragmatic and effectual for linear structures. While it was not very accurate for geometrically nonlinear structures, since more than one iteration was required to get the target.

KEYWORDS

Shape adjustment, Force adjustment, Simultaneously, Force method, Tensile structures, Actuator placement, actuation, bridges.

1. INTRODUCTION

These days, the demanding to build megastructures is globalized; sometimes it required to have few supports in order to provide a large span for example cable-stayed bridges. Nonetheless, there are applications of structural engineering where tolerances of structural shape and internal forces, under changing service conditions, fatigue and are significant, since it has effects on the structure's serviceability limit state and appearance (Saeed, 2014). The structures are composed of beam members, such as arch cable stayed bridges, when they are used for long time or overloaded or due to the harsh environment, some of the beam nodes may undergo a big deflection. Some of the members may also expose stress that close to the allowable stress. Furthermore, cables could face slack, which means they effectively become structurally non-existent, so they would have to be shortened as stated by Manguri *et al.* (2017). In practice, it is almost unavoidable to control one (Displacement or Force) without regard to the other, or at least monitoring on the other to ensure present limits are not breached. In cable structures, this obligation can be seen clearly, for example, when some joints are required to be adjusted meanwhile some cables and struts may suffer enormous internal force, i.e. cables and struts might have keep their limitation of axial force to prevent them against slack and buckling respectively with controlling displacement as stated by Saeed and Kwan (2016a). For dealing with this problem of the techniques of adjustment can be applied.

The idea of controlling was familiarized by Weeks (1984a; 1984b), while Irschik (2002) and Ziegler (2005) reviewed the recent studies in detail, and an analytical procedure was introduced by Haftka and Adelman (1985a; 1985b).The technique of adjustment was defined by Ziegler (2005) and Shea *et al.* (2002) as the process of small changes for reduction, or even elimination of the structural deformation caused by external disturbances. The technique of adjustment can be done by altering member length, which is done by actuators (Haftka and Adelman, 1985a; Edberg, 1987; Burdisso and Haftka, 1990; Kwan and Pellegrino, 1993; Du *et al.*, 2013; Saeed and Kwan, 2016b). Saeed and Kwan (2016b) mentioned that the nodal displacements can be adjusted via actuating some active bars. Passive control strategy was discussed by Irschik (2002).

Adjustments can be classified into three types, external nodal displacements, internal bar force adjustments and a combination of both. For controlling all three types of adjustment joint displacement, bar force and simultaneously control joint displacement and bar force numerous attempts were made. Firstly, regarding the displacement control, Saeed and Kwan

(2016b) controlled external nodal displacement by changing the length of specific bars. Secondly, Kwan and Pellegrino (1993) controlled internal force without regard to displacement in a prestressed structure. Lastly, in terms of simultaneous joint displacement and bar force control, You (1997) worked on shape control of unloaded prestressed structures, i.e. he controlled the displacements of a specific node, while the internal forces in all members were satisfactorily above the desired level without existing external load. Saeed and Kwan (2016b) developed the technique by taking external load into account.

However, the theoretical and experimental nodal displacement and internal bar force control without regard to each other of arch cable-stayed bridges been done by Manguri *et al.* (2017), their control simultaneously becomes indispensable. Therefore, the purpose of this paper is theoretical and experimental nodal displacement and internal bar force control simultaneously of an arch cable-stayed bridge. For this purpose, two structures were manufactured. Structure 1, as shown in Fig. 1, is predicted to behave linearly due to a rigid overhead beam acting as support, whereas Structure 2 is projected to behave as a geometrically non-linear structure, as shown in Fig. 2.

The structure of this work is as follows. The techniques of calculation required amount of actuation for simultaneous internal bar force and external displacement adjustment theoretically is introduced in Section 2. Section 3 shows the detail of physical model of the tested structures. Section 4 presents the results and decision for simultaneous control of nodal displacement and bar force, while, a concluding summary is presented in Section 5.

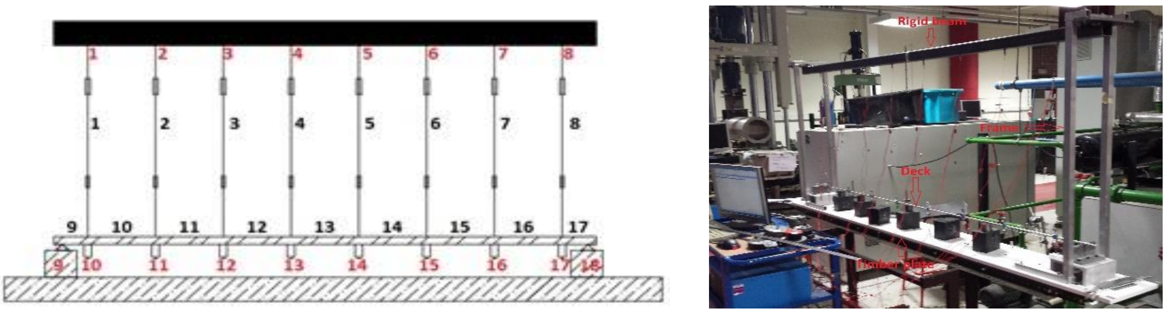

Fig. 1. Cable stayed bridge (Structure 1).

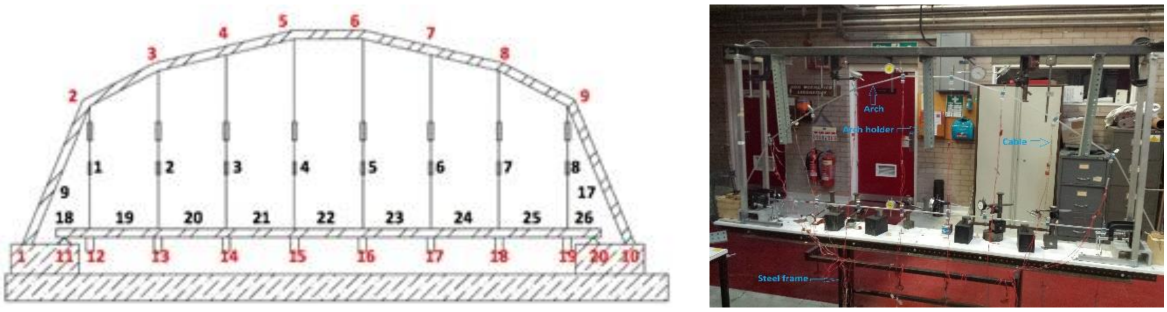

Fig. 2. Cable arch stayed bridge (Structure 2).

2. SIMULTANEOUS INTERNAL BAR FORCE AND EXTERNAL DISPLACEMENT ADJUSTMENT THEORETICALLY.

External nodal displacement adjustment, which can be done by equation (1) (Saeed and Kwan, 2014) is vital for shape critical structures when their shape is made imperfect by unexpected loads or a harsh environment.

$$\boldsymbol{e_o} = \boldsymbol{Y^{+}\{d - d_P\}} \qquad 1$$

where $\mathbf{Y} = \mathbf{B}^{+} - \mathbf{B}^{+}\mathbf{F}\,\mathbf{S}\left(\mathbf{S}^{\mathrm{T}}\mathbf{F}\,\mathbf{S}\right)^{-1}\mathbf{S}^{\mathrm{T}}$, and $\mathbf{d}_{\mathrm{P}} = \left[\mathbf{B}^{+}\mathbf{F} - \mathbf{B}^{+}\mathbf{F}\,\mathbf{S}\left(\mathbf{S}^{\mathrm{T}}\mathbf{F}\,\mathbf{S}\right)^{-1}\mathbf{S}^{\mathrm{T}}\mathbf{F}\right]\mathbf{t}_{\mathrm{A}}$ is the vector of nodal displacements of the structure due only to load, and $\mathbf{d}$ is the resultant nodal displacements after some elongation actuation $\mathbf{e_o}$ has been applied.

While, the theory of internal bar force adjustment is applied to control force inside components of structures via using equation (2) (Saeed and Kwan, 2016b).

$$\boldsymbol{e_o} = \boldsymbol{Z^{+}\left\{t_P - t\right\}} \qquad 2$$

where $\mathbf{Z} = \mathbf{S}\left(\mathbf{S}^{\mathrm{T}}\mathbf{F}\,\mathbf{S}\right)^{-1}\mathbf{S}^{\mathrm{T}}$, and $\mathbf{t}_{\mathrm{P}} = \mathbf{t}_{\mathrm{H}} - \mathbf{S}\left(\mathbf{S}^{\mathrm{T}}\mathbf{F}\,\mathbf{S}\right)^{-1}\mathbf{S}^{\mathrm{T}}\mathbf{F}\,\mathbf{t}_{\mathrm{H}}$, $\mathbf{t}_{\mathrm{P}}$ is the vector of internal force due to the applied load, and $\mathbf{t}$ is the resultant internal forces after some elongation actuation $\mathbf{e_o}$ has been applied.

Equations (1) and (2) provide adjustment for either displacement or force regardless of the other, whereas the combination of them offers the most effective type of adjustment, which can adjust exactly or approximately both nodal displacement and/or bar force at the same time. For the majority of loaded structures, such as bridges, their nodal positions are required to be adjusted which may cause some internal bar forces to reach an ultimate level or slacked (in cables). Therefore, controlling both categories is required to reshape and keep the structure safe in terms of loading.

$$\begin{bmatrix}\mathbf{Y}\\ \mathbf{Z}\end{bmatrix}\mathbf{e_o} = \begin{bmatrix}\mathbf{d} - \mathbf{d_P}\\ \mathbf{t_P} - \mathbf{t}\end{bmatrix} \qquad 3$$

where $\mathbf{e_o}$ is the (total) amount of actuation, required to produce the desired joint displacements and/or internal bar forces, $\mathbf{Y}=\mathbf{B}^{+}-\mathbf{B}^{+}\mathbf{F}\mathbf{S}\left(\mathbf{S}^{\mathrm{T}}\mathbf{F}\mathbf{S}\right)^{-1}\mathbf{S}^{\mathrm{T}}$, $\mathbf{Z}=\mathbf{S}\left(\mathbf{S}^{\mathrm{T}}\mathbf{F}\mathbf{S}\right)^{-1}\mathbf{S}^{\mathrm{T}}$ (Saeed, 2014), **Y** and **Z** are two independent matrices, their sizes depend on the number of joints and bars that decided to be adjusted as well as the number of bars that their length needed to be changed. Regarding their rows, the former matrix relies on the target joint displacements whereas the latter depend on the objective bar forces. In terms of their number of columns, they represent the number of bars that involved to be altered. **B+** is the pseudo-inverse of compatibility matrix (**B**), F is the flexibility matrix, S is the states of self-stress and equal to nulls pace (**A**), and A is the equilibrium matrix. **dp**, **tp** are the vectors of nodal displacements and internal force due only to applied load respectively, $\mathbf{d_P}=\left[\mathbf{B}^{+}\mathbf{F}-\mathbf{B}^{+}\mathbf{F}\mathbf{S}\left(\mathbf{S}^{\mathrm{T}}\mathbf{F}\mathbf{S}\right)^{-1}\mathbf{S}^{\mathrm{T}}\mathbf{F}\right]\mathbf{t_A}$, $\mathbf{t_P}=\mathbf{t_A}-\mathbf{S}\left(\mathbf{S}^{\mathrm{T}}\mathbf{F}\mathbf{S}\right)^{-1}\mathbf{S}^{\mathrm{T}}\mathbf{F}\mathbf{t_A}$ (Saeed, 2014), $\mathbf{t_A}=\mathbf{A}^{+}\,\mathbf{p}$, **A+** is the pseudo-inverse of equilibrium matrix **A**, p is the vector of external loads, d and t are prescribed displacements and internal forces after some elongation actuation $\mathbf{e_o}$ respectively. The application of this technique is presented in Sections 4.1 and 4.2.

3. PHYSICAL MODEL OF THE TESTED STRUCTURES

This section gives the detail about the physical models that were tested. Two structures, one linear and the other geometrically nonlinear were constructed in order to be tested in lab under various case loadings. The main components of the structures were.

Deck beam: The beam is the same for both structures is made of Aluminum and it has a square cross-section 6.5x6.5 mm. The deck beam consists of nine members and ten joints, with the first and the last joints supported on rollers. The distance between the joints is 250mm except at the two ends, where the distance is 125mm.

Cables: Cables are used to transfer loads from the deck beam to the top beams. They are made out from stainless steel, there are eight cables for each structure. The lengths of the cables in Structure 1 are the same. However, for Structure 2 there are four different lengths with each two positional symmetric cables being the same length. The diameter of the cables is 0.25 mm. The cables have EA=9.08kN, while for the beam EA=2.96MN and EI=10.4Nm^2.

4. RESULTS AND DECISION FOR SIMULTANEOUS CONTROL OF NODAL DISPLACEMENT AND BAR FORCE

In this section an experiment was carried out for each Structures 1 and 2, for controlling nodal displacement and bar force controlling simultaneously.

4.1. Structure 1.

All nodes of the deck were loaded with 40.3N downward; this applied load caused external nodal displacements (Table 1, Column 3). Firstly, it is supposed that the joints (except those two adjacent to the supports) of deck surface is required to remain horizontal, and thus all vertical displacements in joints 11 to 16 (Table 1, Column 5) are to be the same amount and their deflection was limited to -3mm.

Table 1 Semultaniouse nodal displacement and bar force control for Structure 1

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
				First Iteration					**Second Iteration**						
Joints	**Cables**	**d_p (mm)**	**t_p (N)**	**Req. d. (mm)**	**e_{o1} (mm)**	**Theo. d. (mm)**	**Exp. d. (mm)**	**Exp. t. (N)**	**Req. d. (mm)**	**Req. t. (N)**	**e_{o2} (mm)**	**Theo. d. (mm)**	**Exp. d. (mm)**	**Theo. t. (N)**	**Exp. t. (N)**
10	1	-2.47	29.9	-	0	-2.28	-2.3	28.5	-	-	0	-2.70	-2.76	33.2	34.0
11	2	-3.81	46.1	-3	-0.97	-3.00	-2.96	49.8	-3	43	1.73	-4.10	-4.08	43.4	42.3
12	3	-3.97	37.8	-3	-0.87	-3.00	-2.97	38.7	-3	42	-0.29	-2.97	-3.17	42.2	42.3
13	4	-4.09	39.1	-3	-1.13	-3.00	-3.03	41.1	-3	41	-0.71	-2.30	-2.29	41.1	41.5
14	5	-4.07	39.3	-3	-1.06	-3.00	-3.09	41	-3	41	-0.46	-2.66	-2.55	41.4	41.0
15	6	-4.03	39.9	-3	-0.95	-3.00	-3.09	41.9	-3	42	0.39	-3.55	-3.33	42.8	42.6
16	7	-3.90	42.8	-3	-1.08	-3.00	-3.00	47.2	-3	43	1.32	-4.03	-4.02	43.7	42.6
17	8	-2.73	34.0	-	0	-2.52	-2.53	27.2	-	-	0	-2.82	-2.91	30.7	31.4
Total actuation (mm)					6.06						4.9				

The first set of $\mathbf{e_o}$ was come from equation (1) and then applied to the physical model, the target was almost attained see Column 8 in Table 1, but problem with high tension in some cables was induced. Due to the necessity of remaining the deck-beam level and limiting forces of the stiff cables to a desired limit as shown in Column11 in Table 1, another attempt become necessary, so second set of $\mathbf{e_o}$ calculated based on equation (3) (Table 1, Column 12).

It can be noticed that after applying the set of actuations, both target displacements and internal bar forces of the structure are almost obtained with a tiny discrepancy (Table 1, Columns 10, 11 14 and 16). This is due to the fact that the request for displacements and internal forces worked against each other on top of that unchanged nodal displacements was a goal after actuation. In terms of theoretical and experimental results of both iterations, it can be said that that the results are coincides (Table 1, Columns 7 to 10 and 13 to 16), thus it can be concluded that the technique of simultaneous displacement and internal bar force is efficient. Therefore, before applying the actuation to the real structure, it can be understood that whether the target is attainable or not from the theoretical results.

4.2. Structure 2.

In this experiment, joints 12 to 19 loaded with 10.3N downward, the loadings are smaller than that of structure 1 because the outer cables undergo high level of tension due to the geometry of the structure. Table 2 provides four iterations of controlling joint displacement and internal bar force simultaneously.

Table 2 Simultaneous nodal displacement and bar force control for Structure 2.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			First Iteration					Second Iteration						
Joints	**Cables**	**d_p (mm)**	**Req. d. (mm)**	**e_{o1} (mm)**	**Theo. d. (mm)**	**Exp. d. (mm)**	**Exp. t. (N)**	**Req. d. (mm)**	**Req. t. (N)**	**e_{o2} (mm)**	**Theo. d. (mm)**	**Exp. d. (mm)**	**Theo. t. (N)**	**Exp. t. (N)**
4y		-5.44	-		-6.62	-12.70		-8			-8.00	-7.3		
5x		-1	-		-5.14	-3.60		-			-3.83	-4		
6x		-1	-		-5.15	-4.66		-			-4.89	-4		
7y		-4	-		-9.59	-12.27		-8			-8.00	-7.69		
12y	1	1	0.5	5.91	0.50	0.15	18.2	-	-	-3.74	1.41	0.95	27.3	28.1
13y	2	-2.45	-1.5	1.87	-1.50	-2.83	11.6	-	-	-0.13	-1.38	-0.42	11.8	11.6
14y	3	-6.05	-3	-4.18	-3.00	-6.98	5	-	-	3.76	-5.45	-3.67	-3.3	0
15y	4	-9.23	-5	-9.13	-5.00	-8.7	13.6	-	-	-0.42	-4.55	-2.9	17.9	17.8
16y	5	-8.67	-5	-9.24	-5.00	-7.73	2.1	-	-	-1.65	-3.08	-2.96	10.9	11
17y	6	-5.66	-3	-8.95	-3.00	-4.02	16.8	-	-	2.87	-1.62	-2.02	2.7	4.1
18y	7	-1.15	-1.5	-1.16	-1.50	-0.77	0	-	4	-3.17	2.26	-0.1	4.0	4
19y	8	0.97	0.5	-0.44	0.50	1.51	35.3	-	-	-4.32	3.34	2.75	40.7	38.4
Total actuation (mm)				40.88						20.06				

Continuous of Table 2

16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
		Third Iteration							Fourth Iteration						
Joints	**Cables**	**Req. d. (mm)**	**Req. t. (N)**	**e_{o3} (mm)**	**Theo. d. (mm)**	**Exp. d. (mm)**	**Theo. t. (N)**	**Exp. t. (N)**	**Req. d. (mm)**	**Req. t. (N)**	**e_{o4} (mm)**	**Theo. d. (mm)**	**Exp. d. (mm)**	**Theo. t. (N)**	**Exp. t. (N)**
4y		-6			-6.00	-5.92			-6			-6.00	-5.73		
5x		-			-4.16	-3.1			-			-3.08	-3.70		
6x		-			-4.16	-3.2			-			-3.18	-3.60		
7y		-6			-6.00	-6.05			-6			-6.00	-5.93		
12y	1	-	-	-1.81	1.64	2.79	34.8	33.8	-	-	0.23	2.74	2.60	33.4	33.0
13y	2	-	-	0	0.73	0.71	5.3	3.7	-	-	0	0.63	0.62	3.9	4.8
14y	3	-	4	-1.3	-1.34	-2.31	4.0	2.0	-	-	0	-2.38	-1.59	1.9	2.4
15y	4	-	-	0	-0.52	-1.24	15.4	14.0	-	-	0	-1.26	-1.23	14.0	15.0
16y	5	-	-	0	-0.77	-1.21	11.7	10.3	-	-	0	-1.17	-1.08	11.3	11.6
17y	6	-	-	0	-0.44	-0.85	5.6	3.6	-	-	0	-0.53	-0.05	-0.1	1.0
18y	7	-	-	0	0.73	1.46	-0.6	0	-	4	-2.11	2.52	2.18	4.0	3.5
19y	8	-	-	-2.2	3.42	3.84	45.5	32.2	-	-	-0.29	4.19	4.06	28.6	39.1
Total actuation (mm)				5.31							2.63				

In the first iteration, after applying the external load the deck suffered non-uniform deflection. In order to reduce and regulate the deflection of the deck $\mathbf{e_{o1}}$ obtained from equation (1) and applied to the physical model. After processing of the actuation by the set of $\mathbf{e_{o1}}$ (Table 2, Column 5), in spite of working the technique the target displacements were not achieved exactly, since the technique based on a linear theory, while the structure is geometrically nonlinear. Due to this adjustment, Cable 7 facing slack was observed. In this case, simultaneous adjustment is unavoidable, consequently $\mathbf{e_{o2}}$ (Table 2, Column 11) through using eqn. (3) was manipulated in the second iteration. In this iteration, displacements of the joints 4 and 7, which were -12.70 and -12.27mm respectively were limited to -8mm (Table 2, Columns 7 and 9), meanwhile to tight Cable 7 (Table 2, Column 8) to be structurally exist. It can be seen that all requirements were almost accomplished (Table 2, Columns 13 and 15), but then again, another cable (Cable 3) violated to slack, thus the third iteration become inevitable.

In the third Iteration, the target was tightening Cable 3 and reducing displacements of joints 4 and 7 from -7.3mm and -7.69mm respectively to -6mm (Table 2, Columns 13, 15, 18 and 19). The set of $\mathbf{e_{o3}}$ (Table 2, Column 20). was calculated again from eqn. (3) then applied to the model of structure. The requirements obtained but Cable 7 again suffered of lack of tension. Fortunately, after applying $\mathbf{e_{o4}}$ (Table 2, Column 27) in the last iteration none of the nodal displacements was out of the required limit and all cables were tight and under permitted level of tension as shown in Table 2, Columns 29 and 31. It can be concluded that the technique of simultaneous displacement and internal force adjustment is pragmatic for geometrically nonlinear structures but more than one iteration could be required. Regarding the theoretical and experimental results, there are very close to each other, thus the theoretical results are reliable. The position of the nodes and internal forces are predictable via theoretical calculation even before applying $\mathbf{e_o}$ to the model structure, and that is an advantageous aspect in practice

5. CONCLUSIONS

In this paper, two physical models (Structure (1) was projected to behave linearly, whereas Structure (2) geometrically designed to act in a geometrically nonlinearly) were constructed. Both structures were tested theoretically and experimentally for the purpose of adjusting joint displacement and internal bar force simultaneously to show the efficiency of the technique for both structures, via the linear technique of adjustment eqn. (3) that was derived by Saeed and Kwan (2016b). It was determined that:

A. Controlling nodal displacement and internal force simultaneously is not as easy as controlling each category alone.
B. The technique to adjust deformation and internal force simultaneously were pragmatic and effectual for linear structures. The accuracy of the technique for geometrically nonlinear structures was not as high as that of linear ones, therefore more than one iterations were required to get the target.
C. The technique can almost achieve the requirements experimentally with a tiny discrepancy between the theoretical and experimental results and this was due to the flexibility of the structure.
D. Before applying the actuation to the real structure, it can be understood that whether the target is attainable or not from the theoretical results. Even if a set of $\mathbf{e_o}$ could not give acceptable results theorotically, the actuated cables could be changed to get better results.
E. The internal bar forces of the structures can be controlled against high tension stress and avoid slack in cables during any attempt to adjust joint displacements simultaneously.

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