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The analysis of load relieving system using sliding cable element

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Abstract

A new structural concept load relieving system is introduced which replaces unaffordable strain by reasonable deformation. A new kind of FEM element cable sliding element is also refer to. Its elementary presentation is given, which has arbitrary number of sliding nodes and satisfies uniform strain assumption. A typical load relieving system model is established applying the sliding cable element and studied under 2 representative load cases. As the results of analysis are reasonable, the correctness and validity of sliding cable element and its application in load relieving system can be proved. Furthermore, the strategy of simulating distributing load by applying concentrated forces on separate nodes of sliding cable element is proved feasible.

Keywords: load relieving system, sliding cable element, large deformation, finite element method, distributing load

1. Introduction

Load relieving system is a new structural concept, which was put forward in 1980s by English researchers, as in Meiboume. [1]. Some extreme load cases must be taken into account in structure design progress to ensure the safety of the building, such as extreme snow load. In this situation, too much cost must be paid for the conditions that may never happen in the whole life of the builiding. Load relieving sysytem may provide an idea to deal with the problem, as in Shan J. [2]. The point of this structural concept is that some kinds of machines were installed in traditional structural system in order to adjust the whole structure according to the loads. The machines work when the loads vary largely and make some parts of the system deform significantly. As a result, unacceptable strain is avoided. It’s the most important advantage of load relieving system that unaffordable strain is replaced by reasonable deformation. Some valuable researches on the application and analysis of load relieveing system have been done in recent years, as in Huang G. [3]. A typical style of load relieving system is shown in figure 1.

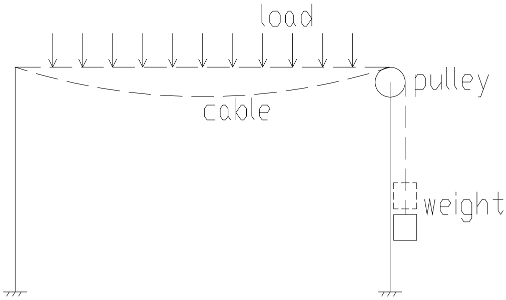

Figure 1: A typical style of load relieving system

Some load relieving system has been used in real structures. Dr Clive Meiboum has designed a garbage station, as in Meiboume. [1]. The torch in the opening ceremony of the Ninth Chinese National Gymkhana Guangzhou 2001 is suspended by a cable sysytem which indicates the principle of load relieving system, as in Cui X. Q. [4]. It is also adopt in a glass wall system in Germany, as in Shan J. [2].

Dynamic relaxation method, as in Shan J. [5] and energy search method have already been applied to solve the mathematical model of load relieving system. But more popular structure analysis method is FEM because of the wide use of commercial FEM program. For most load relieving systems contain cables, geometrical nonlinear iteration is necessary. In general FEM structure analysis, the cables are usually simplified as 2-node straight bar elements separated by adjacent joints, which subject only tension forces. However, in load relieving systems, special type of joint like a pulley is sometimes placed to allow the steel cable to slide freely inside or outside the joint. Though a continuous steel cable may pass through several joints, the tension forces in all cable segments remain a constant. For this situation, the above simplification may cause significant error due to the neglect of cable sliding, as in Cui X. Q. [6]. Some techniques have been presented to consider the cable sliding based on finite element analysis with simplified separate cable elements, as in Li C. X. [7] and Zhang G. F. [8]. They all need manual iteration intervened by engineers, which are time consuming especially for large scale cable structures. Formulating sliding cable element is a more convenient way to simulate sliding cables.

2. Sliding cable element

In this paper, a new kind of multi-node sliding cable element is applied on the analysis of a load relieving system. The element has arbitrary number of sliding nodes and satisfies uniform strain assumption. The principle of virtual work and total Lagrange formulation were used to derive the tangent stiffness matrix of the element. The element was then implemented in commercial finite element software ABAQUS as a user defined element, as in reference [9].

A multi-node sliding cable element is shown in Figure.2. The cable is separated into N-1 segments by N nodes. All nodes can slide along the cable except the two end nodes. The number of degree of freedom of the sliding cable element is 3N. The fundamental kinematic assumption of the multi-node sliding cable element states that (1) the cable remains straight between adjacent nodes; (2) the self-weight of the cable can be ignored and all the loads act directly on the nodes; (3) the strain is uniform along the element, i.e., the strain in all segments of the cable is the same at any time.

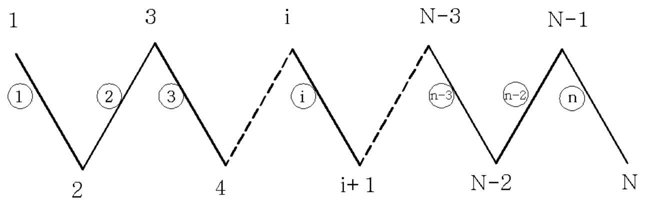

Figure 2: Multi-node sliding cable element

The principle of virtual work for the sliding cable element in total Lagrange formulation (TL) can be expressed as:

$$\int_L S_{11}\delta e_{11} A_0 dL = P_i \delta u_e \tag{1}$$

in which e_{11} is the Green - Lagrange strain, S_{11} is the second Piola - Kirchhoff stress, L is the total length of the cable at initial configuration, P_i and u_e is the node loads and displacements respectively and A_0 is the cross-sectional area of the cable, which is a constant over the entire element length. In the TL formulation, the integration is performed over the initial configuration. Because the strain and stress are assumed to be constant along the element, the integration in Eq. (1) is performed analytically:

$$S_{11}\delta e_{11} A_0 L = P_i \delta u \tag{2}$$

Assume

$$\delta e_{11} = B\delta u_e \tag{3}$$

in which B is a vector of 3N. Substitute Eq.3 into Eq. 2, gives:

$$S_{11} B A_0 L \delta u_e = P_i \delta u_e \tag{4}$$

Considering the randomicity of the variation of node displacements, δu_e, the equilibrium equation of the sliding cable element can be expressed as:

$$S_{11} B A_0 L = P_i \tag{5}$$

The incremental equilibrium equation of the cable element can then be termed as:

$$K\Delta u_e = P_i \tag{6}$$

in which K is the tangent stiffness matrix of the sliding cable element, and

$$K = \frac{\partial(S_{11}BA_0L)}{\partial u_e} = A_0LB^T\frac{\partial S_{11}}{\partial u_e} + A_0LS_{11}\frac{\partial B}{\partial u_e} \tag{7}$$

The second Piola - Kirchhoff stress for the one-dimensional sliding cable element is given by:

$$S_{11} = S_{11}^0 + Ee_{11} \tag{8}$$

in which S_{11}^0 is the initial stress in the cable and E is the Young's modulus. Then

$$\frac{\partial S_{11}}{\partial u_e} = \frac{\partial\left(S_{11}^0 + Ee_{11}\right)}{\partial u_e} = E\frac{\partial e_{11}}{\partial u_e} = EB \tag{9}$$

For the one-dimensional sliding cable element, the Green-Lagrange strain is given by [12]:

$$e_{11} = \frac{l^2 - L^2}{2L^2} \tag{10}$$

in which l is the total length of the cable at present configuration.

For the aim of this paper is to reseach the performence of load releiving system with sliding calbe, the sliding cable element is just a mathematics tool. As well as considering the complexity of the deduce progress and formulation expression, the whole element tangent stiffness matrix is not present here. The detail of the element can be noticed in reference [10].

3. Static analysis of a typical load relieving system with sliding cable element

3.1. Description of the studied structural system

On the base of discussion above, a FEM model of the typical load relieving system is established as shown in figure 3. Two steel columns (column AB and column CD) are set to support the continuous cable. The columns are placed acclivitous to avoid the superposition with the cable. A steel cable is installed from the B end of the column AB, going through the C end of the column BC, hanging a weight at its another end E. The weight is considered as a force and express by a arrow here. The B end of the cable BCE is fixed with the column AB at its B end. A pulley was installed on the C end of the column BC, so the cable can slide through C freely. A end and D end of the columns is fixed on the ground and any movement could not happen.

Figure 3: The studed model of typical load relieving system

The coordinates of point A, B, C, D are respectively (0, 0, 0), (-5, 10, 0), (25, 10, 0), (20, 0, 0). SI units were used when the model established. So one unit in coordinates means one meter. Column AB and column CD are both steel tube of ϕ300×30. And beam element is used to simulate it. The section area of the cable BCE is 0.002 m^2. And the sliding cable element described in this paper is applied to realize the cable-pulley effect. The Young's moduli are $E = 2.06\times10^8\,\mathrm{kN/m^2}$ for the steel tube column AB and CD and $E = 1.95\times10^8\,\mathrm{kN/m^2}$ for the steel cables BCD. The force at point E representing the weight is 40 kN.

Many types of load case can be applied on the structure model. To draw obvious and widely used conclusions, two representative load cases were adopt. Load case 1 is that the middle point of the BC cable segment G suffers a concentrated force F, as is shown in figure 4. The magnitude of F is 15kN. Load case 2 is that the three quarter points of the BC cable segment F, G, H suffer three concentrated forces F at the same time, as is shown in figure 5. The magnitude of F is 10kN.

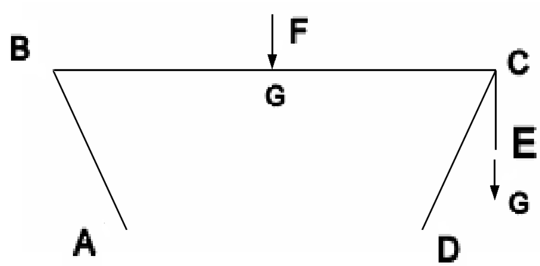

Figure 4: Load case 1

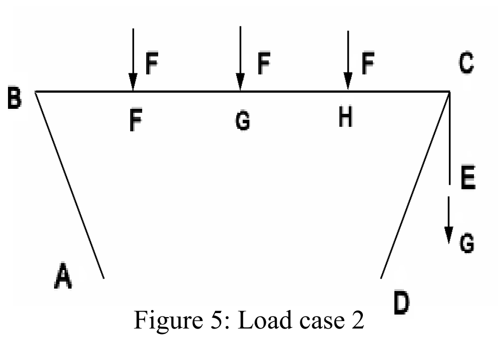

Figure 5: Load case 2

3.2. Analysis result of the model

3.2.1. The result of Load case 1

The deformation progress of the structure develops in the sequence of figure (a), (b), (c), (d) of figure 6 and it is easy to understand. The structure system has not deformed yet in step (a), then the weight G hanged on the cable at E (as is shown in figure 4) works, the columns deform entad, the distance between B and C shrinks, E end of the cable move downward in step (b), then the concentrate force F begins to work in step (c), the influent of concentrate force F reach its peak when the whole system achieve equilibrium in step (d), at this time the deformation of the middle point G of the BC cable segment is the largest and the free end of the cable E move upward significantly.

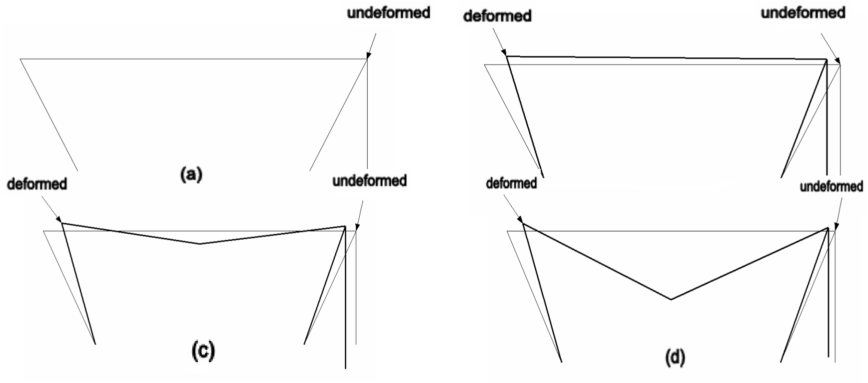

Figure 6: System deformation progress under load case 1

The progress of equilibrium of the structure can be more understandable by listing the magnitude of load F, the stress of cable and the displacements of the very nodes in a table, as is shown in figure 7.

F at point G(KN)	Cable stress(MPa)	Vertical displacement at point G (m)	Vertical displacement at point E(m)
0	19.9981	0.615775	-2.5153
0.4	19.9981	0.564256	-2.51069
0.8	19.99812	0.512704	-2.50566
1.4	19.9981	0.435296	-2.49729
2.3	19.9981	0.319005	-2.48289
3.65	19.9981	0.144099	-2.45712
5.6752	19.99811	-0.11952	-2.40905
8.7124	19.99826	-0.51844	-2.31547
13.2688	19.99984	-1.12689	-2.1256
20.1032	20.0119	-2.06838	-1.7244

30.3548	19.99811	-3.5954	-0.821893
40	19.99815	-5.20196	0.421504

Figure 7: The data table of the structure under load case 1

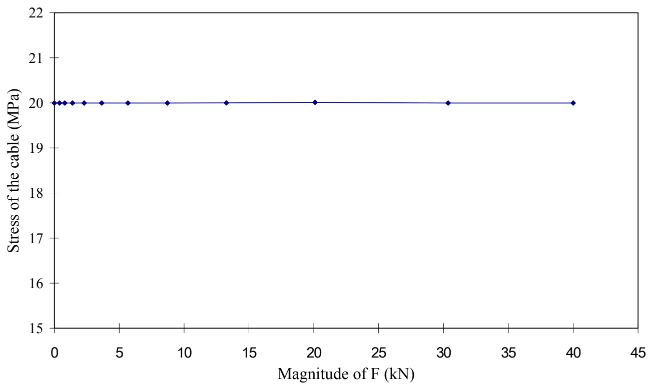

Figure 8: The relationship of F and cable stress under load case 1

Figure 8 and Figure 9 show the variety of cable stress and node displacement under load case 1 respectively. It can be seen that the cable stress remain a constant although the load F varies. It meets the uniform strain assumption of the sliding cable element and prove the correctness of the element in some aspects. The positive displacement means the node move upward, while the negative means downward. It is obvious that point G has a downward displacement and point E move upward because of the load F. It's reasonable in the common concept.

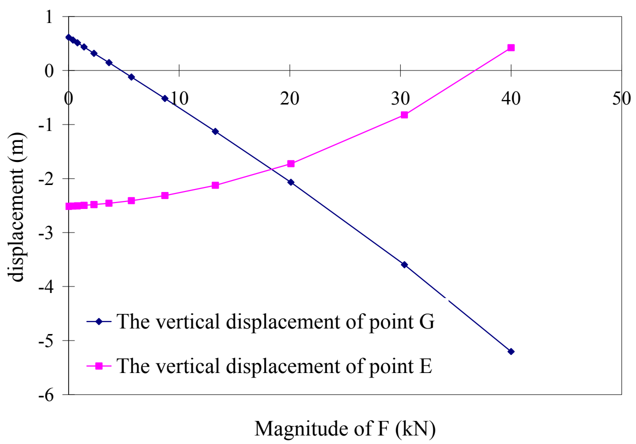

Figure 9: The relationship of F and node displacement under load case 1

3.2.2. The result of Load case 2

Figure10-13 present the corresponding results under load case 2. The conclusion similar to the load case 1 can be drawn. No more new discussion is necessary. But it is remarkable that in load case 1 one single concentrated load is applied to the middle point G of the BC cable segment. In the FEM model of load case 1 only one separate node of sliding cable element is set at point G, while in load case 2 three separate nodes are set respectively at point F, G, H for the concentrated force F to be applied. It is even the reason why load case 2 is adopted. Correctness and validity of using sliding cable element to simulate the distributing loads can be proved if the analysis result under load case 2 is correct and reasonable. The results of Figure10-13 have given satisfying proof that the sliding cable element can solve the distributing load problems effectively. Furthermore, infinite concentrate force can be used to simulate any kinds of distributing load theoretically, even to simulate cable self weight, though the self-weight of the cable is ignored in the assumptions of the sliding cable element.

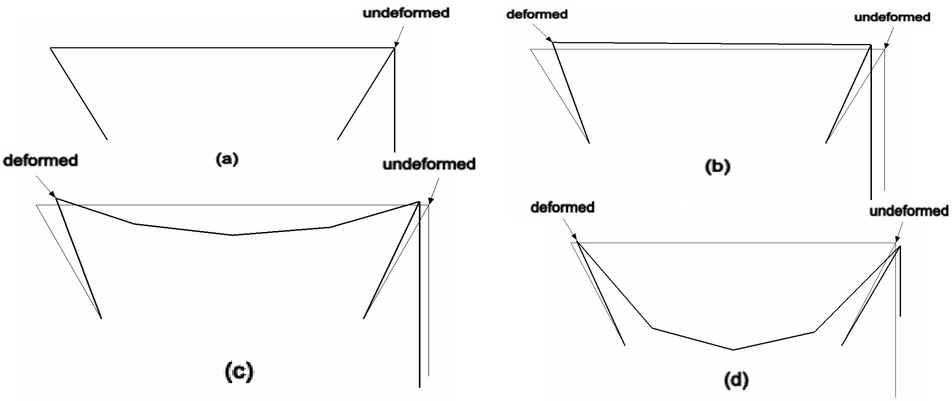

Figure 10: System deformation progress under load case 2

F at point G, F, K(KN)	Cable stress(MPa)	Vertical displacement at point F (m)	Vertical displacement at point G (m)	Vertical displacement at point H (m)	Vertical displacement at point E (m)
0	20.000252	0.681491	0.61577	0.55005	-2.51147
0.4	20.000595	0.636425	0.550235	0.501531	-2.50224
0.8	20.011539	0.591187	0.484504	0.452825	-2.49198
1.4	20.000363	0.52303	0.385581	0.379448	-2.47472
2.3	20.000324	0.420123	0.236484	0.26867	-2.4446
3.65	20.001043	0.26421	0.0112056	0.100857	-2.3898
5.6752	20.007333	0.0267212	-0.330502	-0.154688	-2.28577
8.7124	20.000098	-0.34991	-0.863291	-0.55843	-2.07635

13.2688	20.000150	-0.957684	-1.70691	-1.20738	-1.63408
17.8252	20.003212	-1.64455	-2.63097	-1.93491	-1.01117
22.3812	20.000019	-2.44689	-3.67159	-2.77573	-0.160712
26.9376	20.000175	-3.41782	-4.8811	-3.78025	0.994467
31.4936	20.001192	-4.64341	-6.34393	-5.03014	2.58878
36.05	20.001169	-6.28031	-8.21369	-6.6748	4.88041
40	20.001328	-8.27129	-10.3991	-8.65048	7.84632

Figure 11: The data table of the structure under load case 2

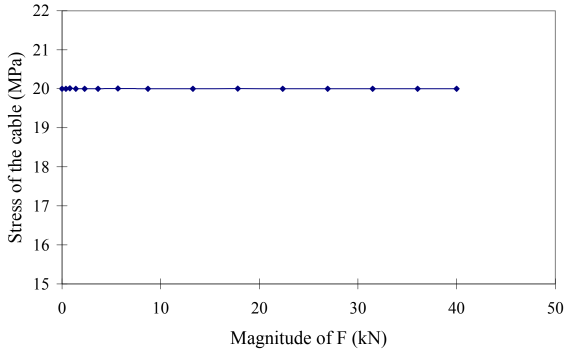

Figure 12: The relationship of F and cable stress under load case 2

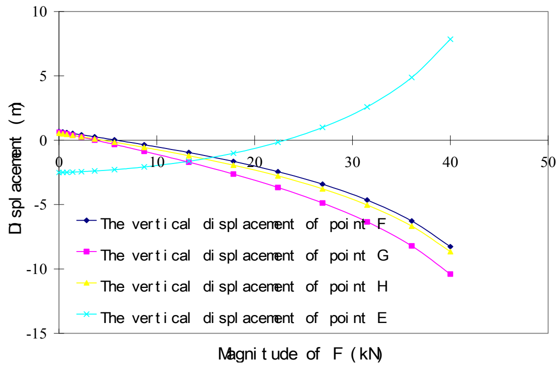

Figure 13: The relationship of F and node displacement under load case 2

4. Conclusions

Load relieving system is a new structural concept. It's the most important advantage of load relieving system that unaffordable strain is replaced by reasonable deformation. Load relieving system usually has something to do with cable structures. Sliding cable element is a new kind of multi-node element. The element has arbitrary number of sliding nodes and satisfies uniform strain assumption. It was applied for the analysis of a load relieving system. Some valuable conclusions can be drawn. (1) Load relieving system can indeed endure large loads by performing significant deformation while keeping the stress remaining constant. (2) Sliding cable element is a correct and valid tool for load relieving system analysis. (3) The strategy of simulating distributing load by applying concentrate force on separate nodes of sliding cable element is feasible and cable self weight can also be simulated in this method.

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