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Basic Mechanical Performance of Pivot Element Bar Included Piezoelectric Material

WANG She-liang[1], TIAN Peng-gang[1,2], ZHU Jun-qiang[1], ZHEN Hong-shan[3]

(1. Key Laboratory of Structure Engineering and Earthquake Resistance of Ministry of Education, Xi'an University of Architecture and Technology, Xi'an 710055, Shaanxi, China; 2. Department of Civil Engineering and Architecture, Shaanxi University of Technology, Hanzhong 723003, Shaanxi, China; 3. Architectural Design and Research Institute of Shandong Province, Jinan 250001, Shandong, China)

Abstract: A new type of pivot element bar included piezoelectric stack material was proposed. Its applicability and suitability for the stability control of steel structure were also expressed. Basic mechanical performances of the piezoelectric spar element under cases of electromechanical coupling and electromechanical decoupling were considered with related structure mechanical theory. At the same time, influence of the length of the piezoelectric material included in the smart active spar element on static stability was quantitatively analyzed by numerical calculation. The results show that the ultimate bearing capacity will increase obviously if considered the electromechanical coupling effect; influence of the length of the piezoelectric material included in the smart active spar element on the stability behavior dose not linearly increase, only in a certain stiffness optimization, the control might be effective.

Key words: piezoelectric stack; pivot element bar; mechanical performance; stability control

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压电材料主元杆件的基本力学性能

王社良[1]，田鹏刚[1,2]，朱军强[1]，甄洪闪[3]

（1. 西安建筑科技大学 结构工程与抗震教育部重点实验室，陕西 西安　710055；2. 陕西理工学院 土木工程与建筑系，陕西 汉中　723003；3. 山东省建筑设计研究院，山东 济南　250001）

摘要：提出了一种实用的新型含压电堆材料的主元杆件，阐述了其应用于钢结构稳定控制的基本工作机理，讨论了该主元杆件在不考虑机电耦合及考虑机电耦合时的极限承载力的改变，同时运用有限元法，讨论了压电主元杆件中含压电堆的长度对其静力稳定性的影响，并进行了数值计算。结果表明：考虑机电耦合能够显著提高主元杆件的极限承载力；主元杆件所含压电堆的长度对静力稳定性的影响并非线性提高，而是必须在特定的刚度优化时才能进行有效地控制。

关键词：压电堆；主元杆件；力学性能；稳定控制

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Biography: WANG She-liang(1956-), male, Xi'an, Shaanxi, professor, doctoral advisor, PhD, E-mail: wangshel@yahoo.com.cn.

0 Introduction

As mentioned in reference [1], intelligent structures are new structure types turned up in last few years with functions of self-perception, self-diagnose, self-recovery and self-strengthening. The key technology for utilizing stability control of smart truss system is how to manufacture pivot element bar, and more important baffles are solved as follows:

(1) Authors connect the single piezoelectric ceramic pieces in series in mechanics and connect them in parallel in electricity, so as to meet the deformation needs of structure outputting large displacement; for the piezoelectric material it is hard to meet the need.

(2) Authors apply compressive forces in advance in the pivot element bar and just let the pivot element bar always in compressive state because piezoelectric ceramic is brittle material and only functions under compressive state, that is to say, it has no actuating use when it is in tension.

(3) On the either side of the pivot element bar, authors install a ball hinge joint braces for weakening the moment effect for the pivot element bar mentioned above which are in-line sensor and actuator and it only can be used as extension-compressive spar, it can't bear moment, etc.

The related reports presented abroad most focus on the intelligent pivot element bar which was made of the pure piezoelectric materials, but for the member made of piezoelectric materials and metal materials, the related papers have never been reported. A new type of intelligent pivot element bar was put forward. Furthermore, authors discussed the feasibility of its application in controlling stability of steel structure. The basic mechanical performance of primary active spar member included the piezoelectric material was also analyzed.

1 Static Stability Equations of Pivot Element Bar Included Piezoelectric Material

As can be seen from reference [2], there is linear relationship between output displacement δ_0 and output force and applied voltage, the correlation coefficients are e_{33} and ke_{33} respectively, and δ_0 is independency to thickness t of piezoelectric materials. The static stability equation of smart pivot element bar under condition of coupling or not is got as follows.

1.1 Decoupling

Based on the simplified calculating model in Fig. 1, we can get

$$E_1 I_1 \frac{d^2 \nu_1}{dx_1^2} + P\nu_1 = 0 \tag{1}$$

$$E_2 I_2 \frac{d^2 \nu_2}{dx_2^2} + P\nu_2 = 0 \tag{2}$$

$$k_1^2 = \frac{P}{E_1 I_1} \tag{3}$$

$$k_2^2 = \frac{P}{E_2 I_2} \tag{4}$$

$$\nu_1 = A\sin k_1 x_1 + B\cos k_1 x_1 \tag{5}$$

$$\nu_2 = C\sin k_2 x_2 + D\cos k_2 x_2 \tag{6}$$

where E_1, I_1 and E_2, I_2 are elastic modulus and inertia moment of aluminum alloy and piezoelectric respectively; ν_1 and ν_2 are deflection of aluminum alloy and piezoelectric respectively.

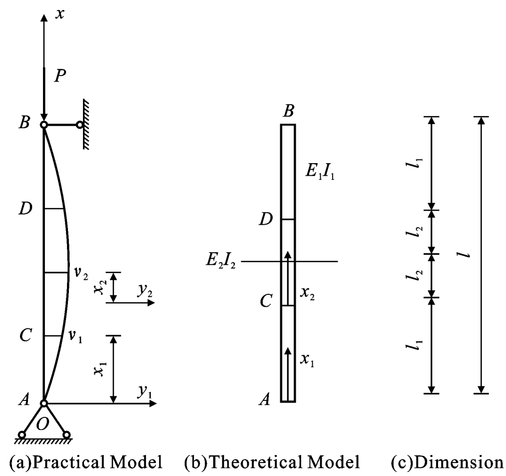

Fig. 1 Simplified Calculating Model of Pivot Element Bar Under Decoupling

图 1 不考虑耦合时压电主元杆件的简化计算模型

According to terminal conditions, we suppose

$$x_1 = 0, \nu_1 = 0 \tag{7}$$

and $x_1 = l_1$, $x_2 = 0$, then

$$\nu_1 = \nu_2 \tag{8}$$

and $x_1 = l_1$, then

$$x_2 = 0, \frac{d\nu_1}{dx_1} = \frac{d\nu_2}{dx_2} \tag{9}$$

$$x_2=\frac{a}{2}=l_2,\frac{\mathrm{d}\nu_2}{\mathrm{d}x_2}=0 \tag{10}$$

then

$$\left.\begin{aligned}&B=0\\&A\sin k_1l_1=D\\&Ak_1\cos k_1l_1=Ck_2\\&C\cos k_2l_2=D\sin k_2l_2\end{aligned}\right\} \tag{11}$$

The static stability equation of pivot element bar included piezoelectric material can be got by simultaneous equations as follows

$$\frac{k_1}{k_2}=\tan k_1l_1\tan k_2l_2 \tag{12}$$

Suppose

$$\frac{E_1I_1}{E_2I_2}=\alpha \tag{13}$$

$$\frac{a}{l}=\frac{2l_2}{l}=\beta \tag{14}$$

then

$$\frac{k_1}{k_2}=\sqrt{\frac{E_2I_2}{E_1I_1}}=\sqrt{\frac{1}{\alpha}} \tag{15}$$

and

$$\left.\begin{aligned}&l_2=\frac{1}{2}\beta l\\&l_1=\frac{1-\beta}{2}l\end{aligned}\right\} \tag{16}$$

$$\sqrt{a}\tan\frac{1-\beta}{2\sqrt{\alpha}}k_2l\tan\frac{\beta}{2}k_2l-1=0 \tag{17}$$

$$P_{\mathrm{cr}}=k\frac{EI_2}{l^2} \tag{18}$$

where

$$k=(k_2l)^2 \tag{19}$$

1.2 Coupling

Pivot element bar will deform a certain degree of extension and compression for embedding piezoelectric material in the middle of spar member under exciting voltage, at the same time, laid common aluminum alloys in either side of the spar member. By perturbation motion output, we can improve extreme buckling load. Considering the characteristic of smart truss system, we can think the spar members as model of axial bearing and deform only with spin joint, accompany with chucking power P_2, based on the simplified calculating models in Fig. 2, so the nodal load P_1 can got by the following equations[3]

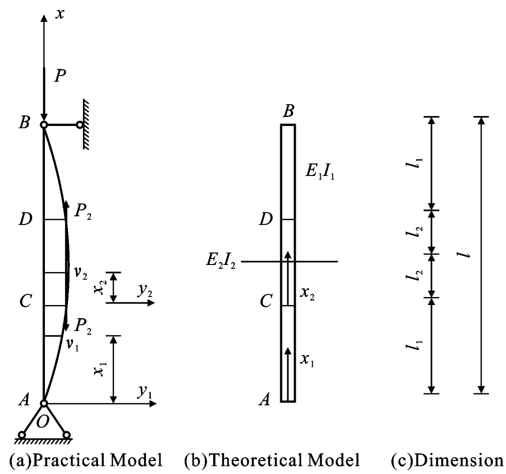

Fig. 2　Simplified Calculating Model of Pivot Element Bar Under Coupling

图 2　考虑耦合时压电主元杆件的简化计算模型

$$E_1I_1\frac{\mathrm{d}^2\nu_1}{\mathrm{d}x_1^2}=-P_1\nu_1 \tag{20}$$

$$E_2I_2\frac{\mathrm{d}^2\nu_2}{\mathrm{d}x_2^2}=-P_1\nu_2+P_2(\nu_2-\nu_D) \tag{21}$$

Suppose

$$\left.\begin{aligned}&\frac{P_1}{E_1I_1}=k_1^2,\frac{P_1-P_2}{E_2I_2}=k_2^2\\&\frac{P_2}{E_2I_2}=k_3^2,\frac{P_2}{E_1I_1}=k_4^2\end{aligned}\right\} \tag{22}$$

Simplified Eq. (20)～Eq. (22), we can get

$$\frac{\mathrm{d}^2\nu_1}{\mathrm{d}x_1^2}+k_1^2\nu_1=0 \tag{23}$$

$$\frac{\mathrm{d}^2\nu_2}{\mathrm{d}x_2^2}+k_2^2\nu_2=-k_3^2\nu_D \tag{24}$$

The numerical solution

$$\left.\begin{aligned}&\nu_1=a_2\cos k_1x_1+b_2\sin k_1x_1\\&\nu_2=c_2\cos k_2x_2+d_2\sin k_2x_2-\frac{k_3^2}{k_2^2}\nu_D\end{aligned}\right\} \tag{25}$$

where $a_2, b_2, c_2, d_2, k_1, k_2$ and k_3 are undetemined parameters respectively; ν_D is deflection of point D.

According to the terminal conditions, if $x_1=0$, then

$$\nu_1=0 \tag{26}$$

and $x_1=l_1, x_2=0$, then

$$\nu_1=\nu_2=\nu_D \tag{27}$$

and $x_1=l_1, x_2=0$, then

$$\frac{\mathrm{d}\nu_1}{\mathrm{d}x_1}=\frac{\mathrm{d}\nu_2}{\mathrm{d}x_2} \tag{28}$$

and $x_2=l_2$, then

$$\frac{\mathrm{d}\nu_2}{\mathrm{d}x_2}=0 \tag{29}$$

By solving Eq. (25)～Eq. (29), we can get the relating coefficients as

$$\left.\begin{aligned} &b_2 = 0 \\ &a_2 \sin k_1 l_1 = d_2 - \frac{k_3^2}{k_2^2} \\ &a_2 k_1 \cos k_1 l_1 = c_2 k_2 \\ &c_2 \cos k_2 l_2 = d_2 \sin k_2 l_2 = \nu_D \end{aligned}\right\} \quad (30)$$

Also the static stability equation of pivot element bar included piezoelectric material can be got by simultaneous equations under considering of coupling as follows[4-9]

$$k_1 \cot k_1 l_1 = \left(1 - \frac{k_3^2}{k_2^2}\right) k_2 \tan k_2 l_2 \quad (31)$$

Suppose

$$\frac{E_1 I_1}{E_2 I_2} = \alpha \quad (32)$$

$$\frac{a}{l} = \frac{2l_2}{l} = \beta \quad (33)$$

then

$$\frac{k_1}{k_2} = \sqrt{\frac{E_2 I_2}{E_1 I_1}} = \sqrt{\frac{1}{\alpha}} \quad (34)$$

and

$$\left.\begin{aligned} &l_2 = \frac{1}{2}\beta l \\ &l_1 = \frac{1-\beta}{2} l \end{aligned}\right\} \quad (35)$$

2 Numerical Example Analysis of Pivot Element Bar Considering Static Stability

2.1 Decoupling

When $E_1 = 7.1 \times 10^{10}$ MPa, $E_2 = 8.807 \times 10^{10}$ MPa, $\alpha = 0.806 \approx 0.8$, and supposing the section area and shape of pivot element bar are the same as common aluminum alloys for application, the inertial moment is equivalent and $\beta = \frac{2l_2}{l}$. The relationship between β and K under decoupling shows as Fig. 3.

2.2 Coupling

The properties of material are equivalent as mentioned above and $\alpha = 0.8$, $\beta = \frac{2l_2}{l} = 0.2$ and $P_2 = 0.1P_1$, the relationship between β and K under coupling shows as Fig. 4.

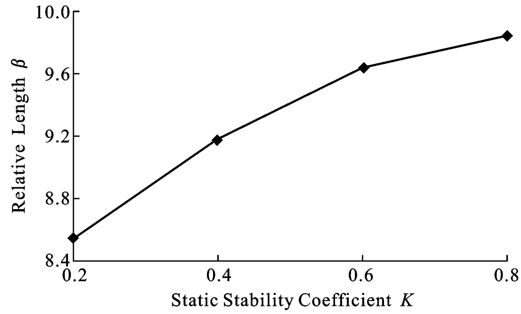

Fig. 3 Relation of Piezoelectric Stack Relative Length β and Static Stability Coefficient K Under Decoupling

图 3 不考虑耦合时压电堆相对长度 β 与静力稳定系数 K 的关系

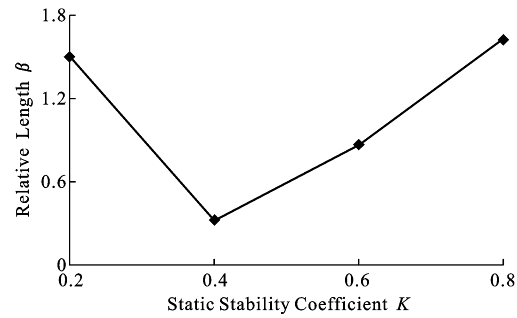

Fig. 4 Relation of Piezoelectric Stack Relative Length β and Static Stability Coefficient K Under Coupling

图 4 考虑耦合时压电堆相对长度 β 与静力稳定系数 K 的关系

$$\frac{k_1}{k_2} = \sqrt{\frac{E_2 I_2}{E_1 I_1}} = \sqrt{\frac{10}{9}\frac{1}{\alpha}} \quad (36)$$

$$\frac{k_1}{k_3} = \sqrt{10\,\frac{E_2 I_2}{E_1 I_1}} = \sqrt{\frac{10}{\alpha}} \quad (37)$$

3 Conclusions

Based on the mechanical properties of piezoelectric materials, authors put forward the static stability equation of pivot element bar included piezoelectric material and the calculating results show as follows:

(1) The buckling load will improve with the increase of the embedded piezoelectric stack's length for higher elastic ratio of piezoelectric materials than common structure steel materials without considering coupling of mechanical and electric performance.

(2) The critical stability factor doesn't have a linear increasing trend with the increase of piezoelectric stack's length under considering coupling

occasion. The main feature shows that the factor will increase when β is 0～0.2 and the factor will decrease when β is 0.2～0.4; the factor will increase insignificantly compared with β is 0～0.2 under condition of β is 0.4～1.0. The phenomenon perhaps shows that it exists optimal configuration of pivot element bars rigidity and needs further study.

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