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The Bionic Lightweight Design of the Mid-rail Box Girder Based on the Bamboo Structure

***Abstract**. Similar structure and mechanics behavior exist between the bamboo stem and the crane's box girder. We studied the relation between the structure parameters and mechanics behavior for the bamboo structure and, it showed that the distance of stems increases by the decreasing of the bending moment and the shear force in the bamboo stem. Meanwhile, the permitted maximum distance between two adjacent stiffeners is established by considering the effects of the distance between two adjacent stiffeners on the rigidity and strength design indexes of the box girder. The strategy of the bionic optimization is to allow variable distances between two adjacent stiffeners so that the box girder has uniformly distributed buckling stability. The optimization is carried out by the finite element nonlinear buckling analysis. On the other hand, through case studies we find that the bionic box girder requires smaller number of stiffeners and smaller amount of steel than the traditional box girder. Moreover, the bionic box girder possesses more uniform buckling stability along the direction of its axis.*

***Streszczenie.** Struktura dźwigaru żurawi jest podbna do struktury bambusa. W artykule analizowano relacje między strukturą bambusa a jego właściwościami mechanicznymi. (**Projektowanie dźwigarów żurawi metodą bioniczną na podstawie analizy struktury bambusa**)*

Keywords: bionics, bamboo, the crane's box girder, optimization.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

1. Introduction

The energy consumption of a crane is usually high due to its heavy box girder. A large amount of research has been done in order to lighten the structure weight, which, of course, will result in lower energy expenditure. Traditionally, for the box girder's lightweight design, the commonly-used steel is replaced by the high strength steel[1],or the structure parameters about the box girder are optimized[2]. However, the above methods are usually implemented by empirical design formulas, leading to a heavier structure weight. Hence, new ideas are needed to lighten the box girder's structure weight, while, at the same time, improve the mechanics behavior for the crane's box girder.

The bamboo is a naturally lightweight plant. It has a naturally optimized structure to bear the environmental load, and its nodes can increase the ability to resist stem bending and buckling. The strength is higher along the exterior surface than along the interior surface. In general, the strength is also higher in those sections closer to the ground[3]. Significant research has been carried out recently on the physical and basic macro-mechanical properties of the bamboo[4-6]. Kim evaluated the mechanical properties by volume fraction of the bamboo fiber, and the test results showed that the strength of the bamboo fiber composite was higher than the poly butylene succinate resin[6]. Via the bamboo microstructure bionic design, Zhou developed a technique to change the form of bamboo from its naturally circular cross-section into a reformed aluminium laminate[7]. Qiao proposed a new method to make ceramics with bionic bamboo structure[8], and Ma found that the bionic, cylindrical shell based on the microstructure characteristics of a bamboo could increase the overall structure efficiency over the commonly cylindrical shell of the same weight by 124.8%[9]. All the previous research didn't involve the bionic design about the macroscopic structure properties of the bamboo. Thus, in this paper, we investigate the relation between the macroscopic structure parameters and the mechanics behavior for the bamboo. The research findings may provide theory basis and design idea for the box girder's lightweight design.

2 Characteristic parameters for the structure of a bamboo stem

Similarity in the three aspects, namely, structure, mechanics behavior and function, is the basis for the bionic design. Understanding thoroughly the similarity between the biological and practical engineering structure is the key problem for the bionic design. Both the bamboo and the box girder belong to hollow structures with high ratio of length to girth and reinforced regions. Besides, they both bear bending moment, shear forces and torques.

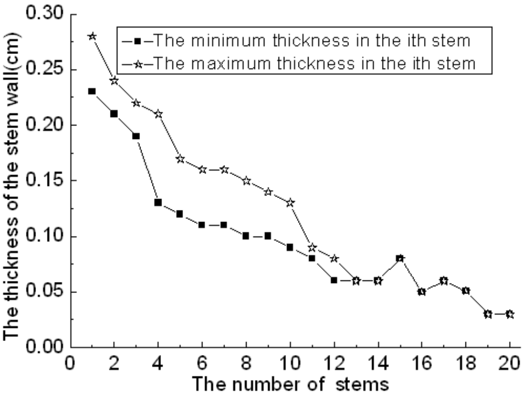

Fig.1. The thickness of the stem wall

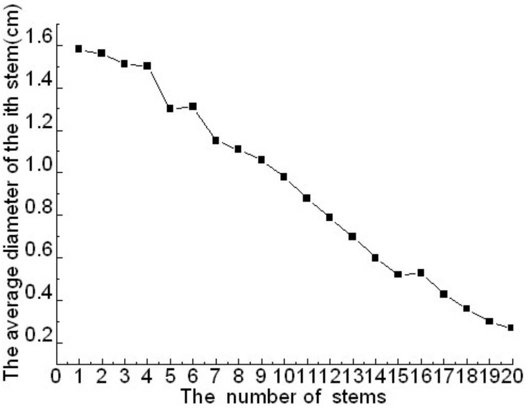

Fig.2. The average diameter of the stem

2.1 Natural structure parameters for the bamboo stem

The stem between two adjacent nodes is numbered as 1, 2, …, i, sequentially from the root to the tip. The stem wall is known to distribute non-uniformly along the stem section.

The stem wall is thicker in the region where the stem is affected by pressure than that affected by tension, as shown in Fig.1. It can be seen that the wall gradually becomes thinner from the root to the tip. It is shown in Fig.2 that the average diameter of the *i*th stem decreases proportionally to the number of stems from the root to the tip, therefore, the bamboo can be approximately considered as a tapering shell structure.

The distance of the *i*th stem is characterized by small in the root and tip, and large in the middle as shown in Fig.3. As the variable cross-section tapering shell structure, the infinite decimal part of the stem in the length direction can be considered as the thin-walled, cylindrical shell structure. It is known that the capacity of the buckling stability is proportional to the radius of the thin-walled, cylindrical shell structure[9],the distance of stems per unit radius is put forward and, its distribution is shown in Fig.4, with a increasing tend from the root to the tip.

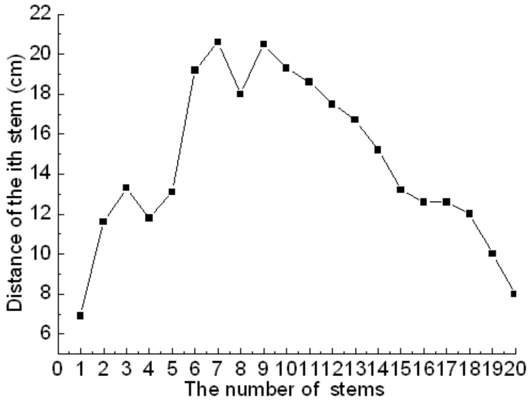

Fig.3. The distance of stems

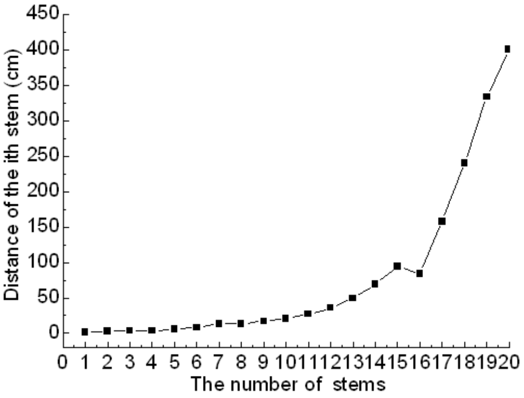

Fig.4. The distance of stems per unit length

2.2 The research of mechanics behavior for the bamboo structure

Let us introduce the coordinate system shown in Fig.5, the tapering shell is selected as the research object, and the angle of spread, θ, for the tapering shell can be calculated by the formula: $\theta=2\pi R/l$. It is assumed that the bamboo is mainly affected by the uniform wind load, which is equal to 1N/m^2. The force in the shadow region can be calculated by the following formula.

$$dF = qdS_{1/2} = [\frac{1}{2}\theta l^2 - \frac{1}{2}\theta(l\text{-}dl)^2]/2 = \frac{\pi R}{2l}[2ldl\text{-}(dl)^2]$$

In the above formula, the length, l, the radius, R, of the stem follow the relation about the angle, α, and α can be obtained by the following formula:

$$\alpha = 2\times arc\sin\frac{R}{l} = 2\times arc\sin\frac{1.58}{581.4} \approx 0.0054$$

Hence, the bending moment and shear force can be calculated by the Eq.1. It is indicated that the bending moment and shear force is proportional to the stem length, L, when L is greater than 0, combined with the Fig.4, the distance of stems per unit radius increases with the decreasing of the bending moment and shear force from the root to the tip.

$$(1)\qquad \begin{cases} M = \int_0^l dM = \int_0^l (\pi R dl)l = \frac{\pi l^3}{3}\sin\frac{\alpha}{2} \\ Q = \int_0^l dF = \int_0^l \pi R dl = \frac{\pi l^2}{2}\sin\frac{\alpha}{2} \end{cases}$$

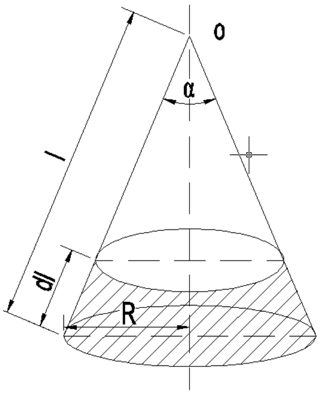

Fig.5. Bamboo's tapering shell structure

3 The research of the mechanics behavior for the box girder

3.1 The maximum bending moment and shear force

The mid-rail box girder is selected as the research object, and only the transverse stiffeners are existed. The mechanics behavior is analyzed by considering the working ultimate position of the hook in the trolley. The important load-bearing part is the main beam for the crane's box girder structure, the main beam is regarded as the simple supported beam in the process of mechanics behavior analysis, and it can be found that the maximum shear force and bending moment are different in different sections when the wheels of the trolley move along the main beam.

3.2 The effect of the distance of beams on the structure rigidity and strength

The structure rigidity and strength are the important design indexes for the crane's main beam. Among the relevant factors that affect the perpendicular rigidity and the overall bending stress, only the section inertia moment, I, can be slightly affected by the distance of beams between the two adjacent stiffeners, which is called simply as the distance of beams, and hence, the effect of the distance of beams on the rigidity and the overall bending stress in the main beam can be ignored.

The local bending stress in the rail can be calculated by the continuous beam on many supports, and the related formula is given as follows[10]:

$$(2)\qquad \sigma_g = \frac{(P-N)S_i}{6W_g} \le [\sigma_g]$$

where, P represents the concentrated wheel pressure in the trolley, the stiffener is numbered as 1, 2, …, i, sequentially from the middle section of the main beam to the end section, S_i represents the distance of beams between the ith and i+1th stiffeners, N represents the pressure in the top flange plate transformed from the rail, W_g represents the section modulus of the rail, and $[\sigma_g]$ represents the allowable stress of the rail. It can be concluded that the local bending stress in the rail is linear to the distance of beams.

Assuming that the top flange plate is affected by N in the form of uniform load, its strength checking can be expressed by the Eq.3[10].

$$\left.\begin{aligned}&\sigma_W+\sigma_z\le[\sigma]\\&\sqrt{(\sigma_W+\sigma_z)^2+\sigma_x^2-(\sigma_W+\sigma_z)\sigma_x}\le 1.1[\sigma]\end{aligned}\right\}\tag{3}$$

where, σ_W、σ_z and σ_x represent the overall bending stress, local bending stress parallel and perpendicular to the axis line of the main beam, respectively, therefore, the distance of beams is closely related to the strength design of the top flange plate.

4. The uniform buckling stability design of variable distances for the crane's box girder

In the traditional method, all the stiffeners in the main beam are laid out in the approximately same distance. The similar structure and mechanics behavior are existed between the bamboo and crane's box girder. The relation between the structure parameters and mechanics behavior for the bamboo is used to carry out the bionic design on the main beam of the crane, achieving the uniform buckling stability design of variable distances for the crane's box girder and making the lightweight design of the box girder.

Because the main beam is completely symmetric with the middle section of the main beam, only the main beam ranging from 0 to $L/2$ is selected as the research object. When the distance between two stiffeners, S_i, is greater than the axle gauge of the trolley, b, the local bending stress will be large in the local region S_i, where the rail and top flange plate are simultaneously affected by the wheel pressure, P_1 and P_2 in the trolley. In order to guarantee that the local region can be affected by single wheel pressure in the trolley, S_i is assumed to be less than b. Some definitions are given as follows to carry out the bionic design.

(1) The bias proportion of the uniform buckling stability design

The buckling stability corresponding to the initial distance, S_1, in the middle section of the main beam is referred to evaluate whether the buckling stability corresponding to other distances of beams meet the uniform buckling stability design demand or not. Let us assume that P_1 and P_i^n is denoted by $P(S_1)$ and $P(S_i^n)$, respectively, where S_i^n represents the distance in the nth searching process for the ith stiffener, and S_i^1 is equal to the permitted maximum distance，which is less than b and must meet the structure rigidity and strength design demands. The bias proportion is defined by the formula: $r(S_i^n)=(P_i^n-P_1)/P_1$, and it is regarded as the indicator to weigh the distance of beams to meet the uniform buckling stability design or not. When r ranges from $-\alpha\%$ to $\alpha\%$, it means the solution converges. When r is more than $\alpha\%$, it means the distance of beams is a little smaller and the buckling load is a little bigger. When r is less than $\alpha\%$, it means the distance of beams is a little bigger and the buckling load is a little smaller.

(2) Searching operator related to the distance's increasing

$S_i^n=1/2(S_i^{n-1}+S_{i\min}^{n-2}), i>1, n>1,$ when $r(S_i^{n-1})$ is more than $\alpha\%$, the distance needs to be increased. $S_{i\min}^{n-2}$ represents the minimal distance of beams corresponding to the bias proportion that is less than $-a\%$ in the previous n-2 times searching process for the ith stiffener, and it can be given by: $S_{i\min}^{n-2}=\min\{S_i^1,S_i^2,...,S_i^{n-2}\}\big|r=(-\infty,-a\%)$.

(3) Searching operator related to the distance's decreasing

$S_i^n=1/2(S_i^{n-1}+S_{i\max}^{n-2}), i>1, n>1,$ when $r(S_i^{n-1})$ is less than $\alpha\%$, the distance needs to be decreased. $S_{i\max}^{n-2}$ represents the maximum distance of beams corresponding to the bias proportion that is larger than $a\%$ in the previous n-2 times searching process for the ith stiffener, and it can be given by:

$$S_{i\max}^{n-2}=\max\{S_i^1,S_i^2,...,S_i^{n-2}\}\big|r=(a\%,+\infty),$$

and the initial value $S_{i\max}^0=0.$

As

$$S_i^n=1/2(S_i^{n-1}+S_{i\min/\max}^{n-2})\le 1/2(b+b)=b,$$

the distance searching operator can guarantee the local region, S_i, is affected by single wheel pressure.

(4) Local convergence criterion for the distance of beams

When $r(S_i^1)$ is more than $-\alpha\%$, the searching process directly turns to the searching process for the next distance of beams, otherwise, the process goes on to follow the step.

When r is less than $-\alpha\%$, the searching operator is used to increase the buckling load. As the dichotomy is used in the searching operator, it is possible that the distance adjusted by the searching operator is so small that r is more than $\alpha\%$. Here, the searching operator is needed until the process meets the design demands.

When r is more than $\alpha\%$, the searching operator is used to decrease the buckling load. As the dichotomy is used in the searching operator, it is possible that the distance adjusted by the searching operator is so big that r is less than $-\alpha\%$. Here, the searching operator is needed until the process meets the design demands.

When r ranges from $-\alpha\%$ to $\alpha\%$, the process meets the uniform buckling stability design demand, and turns to the searching process for the next distance of beams.

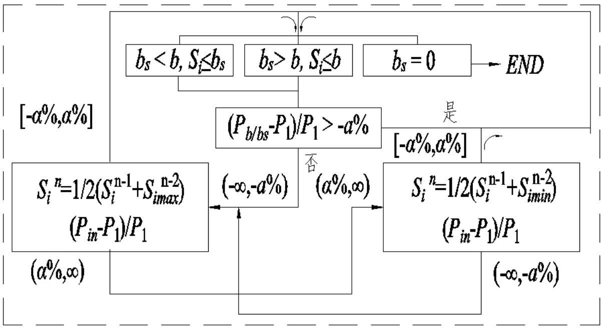

Fig.6. The uniform buckling stability design strategy of variable distances of beams for the crane

(5) Stopping convergence criterion

The remaining distance, b_s, can be calculated by the formula: $b_s=L/2-(S_1+S_2+\ldots S_{i-1})$. The permitted maximum distance of beams will be the lower value between b_s and b, and when b_s is 0, the searching process ends. The uniform buckling stability design strategy for the variable distance of beams about the box girder is shown in Fig.6.

5 The optimization case for the mid-rail box girder

Following the design strategy as shown in Fig.6, the optimization iteration is made for a mid-rail girder to check the advantage of the bionic design by the nonlinear buckling analysis, the length of its main beam, L, is equal to 16.5m, the axle gauge of the trolley, b, is equal to 1.1m, and the wheel pressure, P_1 and P_2, in the trolley is equal to 17750N.

5.1 The material and geometry nonlinear buckling analysis

The box girder is made by the Q235 steel, the material model of the bilinear kinematic hardening is used to simulate the material property. It means that the material follows the elastic modulus, E, which is equal to 2.1×105MPa, in the process of elasticity deformation, and the material follows another elastic modulus, $0.03E$, in the process of plasticity deformation. In order to model accurately the buckling stability, the geometry initial defects, such as bending and manufacturing defect, is considered. The initial defect for the plate is obtained by the lowest-level local modal by modifying the node coordinate system.

5.2 The comparisons between the traditional and bionic structure

The maximum distance of beams can be equal to the axle gauge of the trolley, b, by the calculation of Eq.2 and 3. The bias proportion of the uniform buckling stability design is set to 5% to carry out the bionic optimization design. The number of the stiffeners in the traditional and bionic box girder is 15 and 10, respectively, as shown in Fig.7 and Fig.8. The distance of beams in the traditional and bionic box girder ranges between the 0.445~0.53m and 0.55 ~1.1m, respectively, and the 7th, 8th, 9th and 10th distance of beams in the bionic box girder are 1.1, 1.1, 1.1 and 0.595m, respectively. For one thing, the bionic box girder can decrease the number of the welding line and improve the fatigue life of the box girder structure. For another thing, the bionic box girder uses less steel consumed by the stiffener, which can reduce the structure weight of the box girder by 160.14 kg and make the structure bionic lightweight design for the crane.

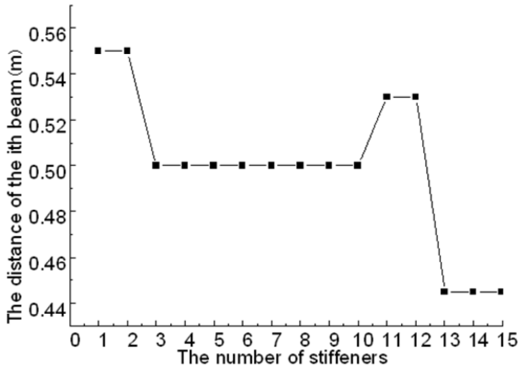

Fig.7. The distance layout between two adjacent stiffeners in the traditional box girder

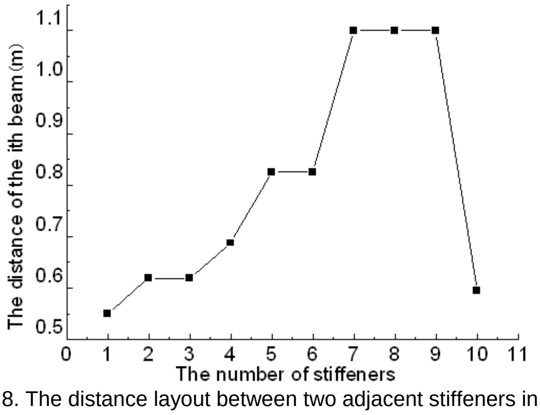

Fig.8. The distance layout between two adjacent stiffeners in the bionic box girder

As the effect of the welding residual stress on the buckling stability is ignored, the buckling load value is a little larger. It is shown in Fig.9 and Fig.10 that the buckling load increases with the decreasing of the distance between the stiffener and the middle section of the main beam. After the bionic optimization for the box girder, the ratio of buckling load in the middle of beams among 1st and 7th is almost the same, and their values range between 6.65 and 7.35. The ratio of buckling load in the 8th and 9th stiffener is 7.8 and 9.2, respectively. The 10th stiffener is regarded as the remaining distance, b_s, and b_s is less than b and equal to 0.595m. The ratio of buckling load corresponding to b_s is 18.50, then r is more than a%, and the searching process ends.

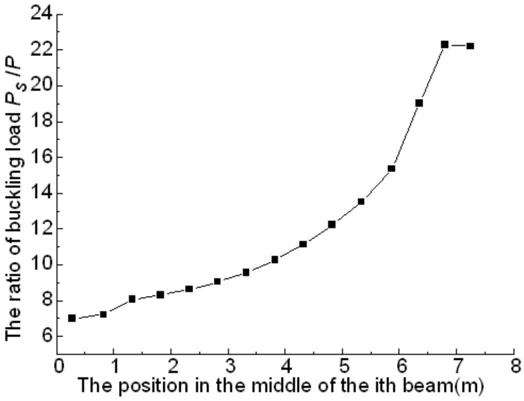

Fig.9. The ratio of buckling load Ps/P for the traditional box girder

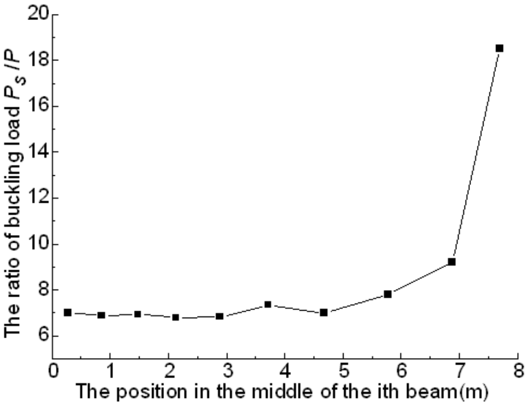

Fig.10. The ratio of buckling load Ps/P for the bionic box girder

6 Conclusion

Aimed at the lightweight design problem of the mid-rail box girder, the relation between the structure parameters and mechanics behavior is investigated for the bamboo. The relation is used to guide the bionic design for the stiffener layout in the box girder. The research results not only can prompt the wide using of the bionic optimization design for the practical engineering structure, but also can perfect the lightweight design theory system for the crane's box girder.

1) The diameter of stems decreases almost linearly from the root to the tip and, the stem is considered as the tapering shell to make the mechanics behavior analysis. The findings indicate that the distance of stems per unit length increases with the decreasing of the bending moment and the shear force in the stem section.

2) The searching operator related to the variable distances and the converge criterion are defined to carry out the bionic optimization design. The permitted maximum distance of stiffeners is obtained by considering the crane's stiffness and strength design indexes.

3) After the bionic optimization, the number of the stiffeners changes from 15 to 10, the distance of beams ranging between 0.445 and 0.53m changes to 0.55 and 1.1 m, and the maximum ratio of buckling load changes from 22.29 to 18.50. Therefore, the structure weight of the box girder can be reduced by 160.14 kg.

4) Bionic box girder can decrease the number of the welding line, which can improve the fatigue life of the box

girder. Furthermore, the bionic box girder uses less steel used by the stiffener, making the lightweight design on the bionic optimization.

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REFERENCES

[1] Kallage P., Herzog D., Ostendorf A., Mechanical properties of laser MAG hybrid welded high strength steels,Welding in the World,52(2008), 109-115

[2] Sun, C. L., Tan Y., Zeng J. C., The structure optimization of main beam for bridge crane based on an improved PSO, Journal of Computers, 6(2011), No.8,1585-1590

[3] Tan T, Rahbar N., Allameh S. M., Mechanical properties of functionally graded hierarchical bamboo structures. Acta Biomaterialia, 7(2011), No.10,3796

[4] Chung K.F., Yu W.K., Mechanical properties of structural bamboo for bamboo scaffoldings. Engineering Structures, 7 (2011), 429–42

[5] Silva E. C. N., Walters M. C., Paulino G. H., Modeling bamboo as a functionally graded material: lessons for the analysis of affordable materials, Journal of Materials Science, 41(2006), No.21,6991–7004

[6] Kim Y. H., Yoon S. W., Yang D. H., An S. J., A Study on the Mechanical Properties of Bamboo Fiber Reinforced Composites in Comparison with Matrices Advanced Science Letters, 4(2006), No.4-5,1574–1577

[7] Zhou B. L., Bio-inspired study of structural materials. Materials Science and Engineering, 11(2000), No.1,13–18

[8] Qiao G. J., Ma R., Cai N., Zhang C. G., Jin Z H. Microstructure transmissibility in preparing SiC ceramics from natural wood. Journal of Materials Processing Technology, 120(2002), No.1-3,107–110

[9] Ma J. F., Chen W. Y., and Zhao L., Elastic buckling of bionic cylindrical shells based on bamboo,Journal of Bionic Engineering, 5(2008), No.3,231–238

[10] Wang J. N.,and Yu. L. F., Metal Structure for the hoisting machinery, China Railway Press, Bei Jing (2002),142-146

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