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Mechanical Behavior of Hinge Lozenge Grid Structure

Zhong Li¹, Shuai Wang², Kaifa Zhou¹, Qianwen Tan¹ and Huolei Feng¹

1.School of Civil Engineering, Chongqing Jiaotong University; 2.College of Intelligent Manufacturing, Chongqing Vocational College of Transportation. 66 Xuefu Avenue, Nanan District, Chongqing, China.

Email: lizcyc@sina.com

Abstract. There are two phenomena in the inflation process of the existing stent, dogboning and axial expansion, which will shorten the life of the stent and lead to the failure of stenting. Firstly, The hinge lozenge grid structure with negative Poisson's ratio was reported. Secondly, the process of inflation and springback of stent were simulated based on finite element method in order to analyse its expansion, axial expansion ratio and resilience rate. It is demonstrated that hinge lozenge grid structure with symmetrical deformation exhibits "full-scale expansion" structural properties. Besides, the diameter of inflated stent is twice as much as initial after expansion. Also, it shows axial elongation as well as increasing axial expansion ratio. The displacement changes obviously with the increase of pressure with other conditions unchanged. This new structure not only improves the radial support performance of intravascular stents significantly, but also overcomes the shortage of traditional stents, which provides a new idea for the design and optimization of intravascular stents.

1. Introduction

Until now, stenting is a common way to treat coronary artery disease, which supports the vessel wall by placing intravascular stent in the stage of coronary artery stenosis to keep the blood flow unblocked. Therefore, it becomes a hot topic to investigate the mechanic properties of intravascular stents. In 1994, PTCA was simulated by finite element method(FEM), and the results of finite element simulation were fitted with experiment results[1], which showed the function of FEM in the stent analysis. A simplified nickel-titanium self-expanding stents was proposed firstly in 1997, and the change of stress was studied under compression[2]. Balloon dilatation experiment in vitro is carried out on the stents with different design and materials, and a stent-balloon model is established to simulate the process of stent dilatation, which is used to study the expansion characteristics of coronary stents[3]. The continuing researches on stent are carried out in the follow-up study, articles [4-7] all put forward their own simulation methods of stent expansion. However, none of these simulations takes the role of balloons into consideration, and the pressure is directly loaded on the inner surface of the stent to expand it. An advanced design of stent-balloon model was proposed in article[8] to overcome the dogboning of stent during balloon expansion, which causes the phenomena that the middle expands after edge and foreshortening. The advanced design is tested by FEM and experiment, which shows agreements between simulation and experience.

The materials with negative Poisson's ratio are rapidly emerging at the frontier of scientific and technological innovation due to their interesting property of negative Poisson's ratio. Many new novel auxetic structures are explored to exploit in a wide range of applications. Two novel auxetic structures, re-entrant star-shaped honeycomb and star-arrowhead honeycomb, are proposed and their in-plane crushing behavior are studied systematically[9][10]. Besides, two novel auxetic cellular structures with negative Poisson's ratio, high Young's modulus and yield strength simultaneously are proposed,



and their mechanical properties are predicted by FEM and experiments respectively[11]. In addition to combine two kinds of auxetic structures, a novel structure with variable Poisson's ratio is proposed with the combination of negative and positive Poisson's ratio, which deforms smoothly in impact loading and absorb the impact over a longer time than comparable uniform structures with positive Poisson's ratio[12].

Based on the research of scholars at home and abroad, this paper proposes hinge lozenge grid structure with negative Poisson's ratio aiming to the phenomena of dogboning and foreshortening. The expansion behavior of stent is simulated by numerical method to explore the mechanical behavior of the structure in the process of expansion and unloading, which provides a new design idea for the future development and application of intravascular stent.

2. Finite Element Analysis

2.1. Stent Geometric Model and Material Parameters

A novel structure with negative Poisson's ratio is proposed in the article, which is hinge lozenge grid structure, whose configuration is shown in Figure 1. The cell displayed in Figure 1(a) is described with 6 parameters, where $l = \pi/6\text{mm}$ is the length of cell structure, $\alpha = \arctan(1/2)$ is the angle between the tilted ligament and the parallel ligament, $t = 0.01\text{mm}$ is the ligament thickness, $R_{outer} = 0.05\text{mm}$ is the outer radius of bigger circle and $r_{outer} = 0.03\text{mm}$ is the outer radius of smaller one. $b = 0.01\text{mm}$ is the thickness of structure. Figure 1(b) is the 2D hinge lozenge grid stent structure $12 \times l$ by $6 \times l$, which is the arrays of cell structures.

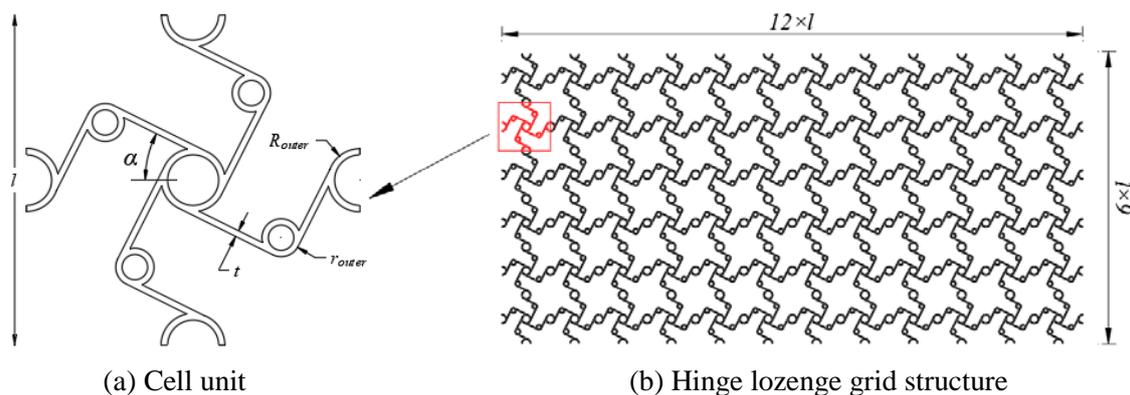


Figure 1. Geometrical layout of the 2D hinge lozenge grid structure.

Figure 2(a) is the cylindrical shaped stents fabricated from Figure 1(b) with radius 1mm. 1/6 of the stent is taken as study object because of its axial symmetry.

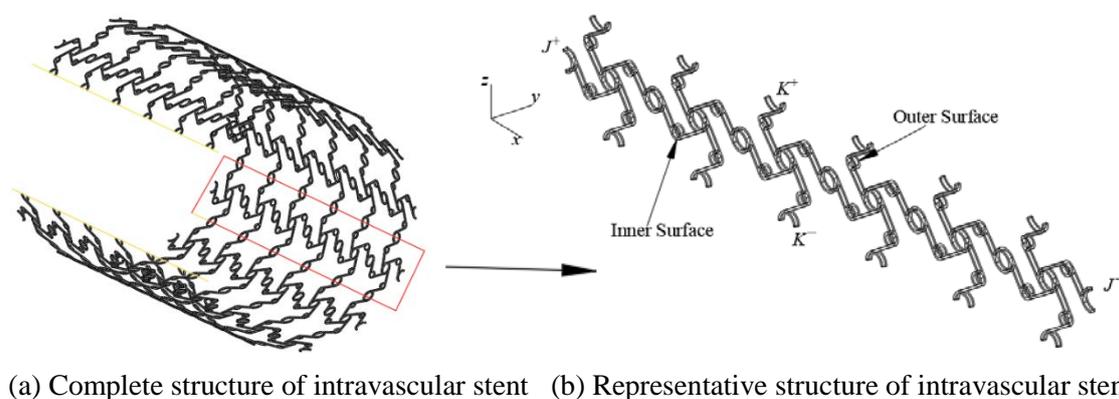


Figure 2. Hinged lozenge grid stent.

In this paper, COMSOL Multiphysics is used for finite element simulation analysis of this stent. In order to better simulate the real working conditions, the material adopts self-defined material parameters, which is listed in Table 1.

Table 1. Material parameters.

Young's Modulus $E(\text{GPa})$	Poisson's Ratio μ	Density $\rho(\text{Kg/m}^3)$	Initial Yield Stress $\sigma_s(\text{MPa})$	Tangent Modulus $E_t(\text{MPa})$
1.93	0.27	7050	207	692

Free tetrahedral method is used in mesh generation. The maximum element size is 0.3mm, the minimum element size is 0.01mm, maximum element growth ratio is 1.5, and the number of tetrahedra is 11375.

2.2. Boundary Conditions and Loads

Studying the expansion of intravascular stent is a three-dimensional problem, and its geometric shape, constrained conditions and loads applied in the stent are completely symmetrical in its radius and axial direction. The planes on the boundary K^+ and boundary K^- are all circumferential symmetric planes with symmetrical constraints. Boundary J^+ and boundary J^- are axial boundaries, and planes on boundary J^+ are exerted symmetrical constraints while planes on boundary J^- are free. Plane Outer is free and plane Inner is surface stress with uniform distributed radial pressure P . There is a lineal relationship between load Q and time as follows:

$$Q = \begin{cases} Pt, 0 \leq t \leq 1 \\ -Pt + 2P, 1 \leq t \leq 2 \end{cases} \quad (1)$$

3. Results and Discussion

3.1. Numerical Result

The inflation of the hinge lozenge grid stent and the one after the pressure were studied, which the plastic deformation is demonstrated. The deformed configurations is drew on the undeformed shapes in Figure 3(a). Regarding the numerical models in Figure 3(a) and (b), the displacement of stent under internal pressure in the process of expansion is drew on. The blue regions correspond to the elastic deformed configurations, whereas the red ones correspond to the plastic configurations is shown in the in Figure 3(b). Firstly, there is obvious dogboning. Secondly, there are obvious expansion and elongation in the axial direction in the process of expansion along the radius direction. Meanwhile, most of the plastic deformation is retained according to Figure 3(a) and the expansion deformation is obvious. The full-scale expansion occurs in hinge lozenge grid stent.

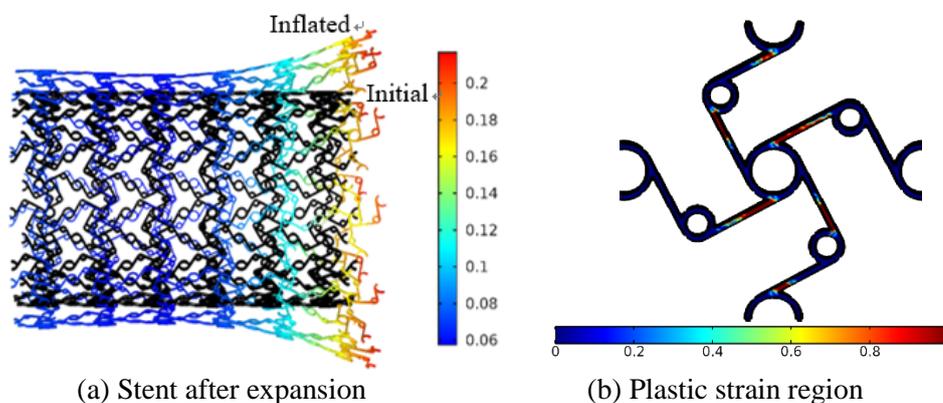


Figure 3. Stent after expansion and plastic strain region.

The stent deformation is represented in Figure 4(a). In the following discussions, the expansion uniformity d , the axial expansion ratio l , the metal surface coverage rate κ and the springback rate ξ will be used to reveal more details to evaluate the dogboning and the axial expansion effect. The uniformity of stent expansion is used to describe the rate between maximum diameter and minimum during the stent expanded and no loaded. When the stent expands, it will appear non-linear shortening. Formula (2) is used to calculate the uniformity of stent expanding, and the diameter of stent is grown up to the maximum diameter, there will be a somewhat elongation and shortening. Formula (3) is used to calculate the axial expansion rate. Except stent elongation and shortening, the ability of resistance to deformation depends on the surface area of the stent. Area coverage is the ratio of prosthetic surface(PS) to open surface(OS), as shown in formula (4). Large deformations, including elastic and plastic deformations, occur after the stent expands through balloon. When the balloon is relieved, the elastic deformation part will be rebound. The springback rate is calculated by formula (5).

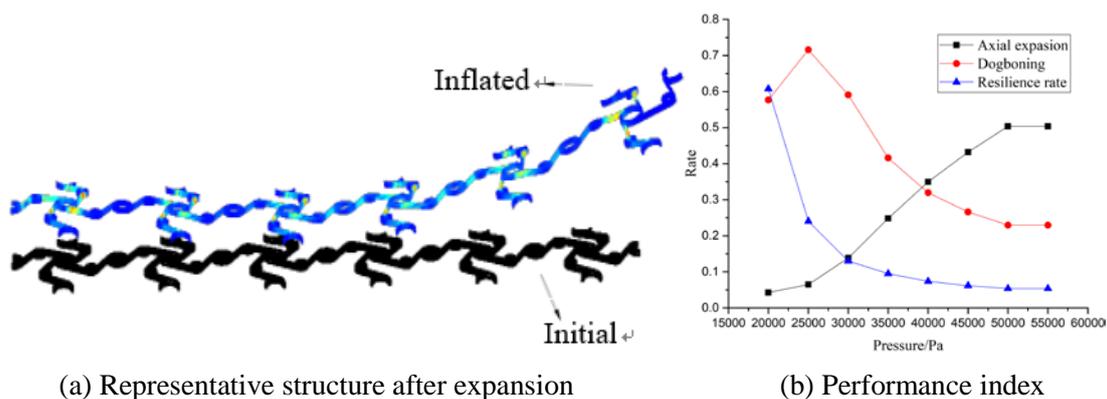
$$d = \frac{r_{distal} - r_{central}}{r_{distal}}. \quad (2)$$

$$l = \frac{L_0 - L_{load}}{L_0}. \quad (3)$$

$$\kappa = \frac{S_{PS}}{S_{OS}}. \quad (4)$$

$$\xi = \left(1 - \frac{D_{final}}{D_{inflated}} \right). \quad (5)$$

Where r_{distal} is stent edge radius, $r_{central}$ is stent middle-part radius in formula (2). L_0 is initial length and L_{load} is length of post-loading in formula(3). S_{PS} is metal area of stent and S_{OS} is the area of cylinder which is surrounded by the stent in formula(4). D_{final} is stent maximum diameter during expansion and $D_{inflated}$ is stent diameter after rebound in formula(5).



(a) Representative structure after expansion

(b) Performance index

Figure 4. Representative structure after expansion and performance index.

3.2. Results Analysis

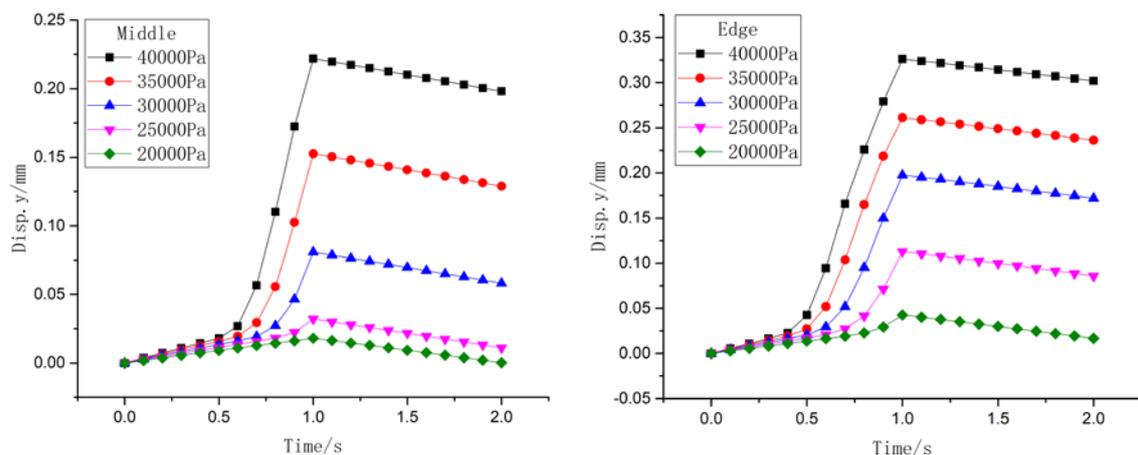
The force versus rate curves of the expansion uniformity d , the axial expansion ratio l , the metal surface coverage rate and the springback rate are extracted from the numerical results in Figure 4(b). The dogboning phenomenon is obvious in the figure, which is consistent with numerical results in Figure 4(a). The maximum expansion uniformity reaches 0.74 when the pressure value is 25 000 Pa. The dogboning phenomenon of the stent decreases continuously with the pressure value increasing. With the pressure increasing, the elastic limit of the material has been exceeded with the displacement of hinge lozenge grid structure rising and the material comes into the plastic phase. Because of the accumulation of plastic strain, the displacement increases slowly and the proportion of expansion

uniformity drops. The axial expansion ratio versus pressure falls in Figure 4(b). It also proves that the elasticity of the hinge lozenge grid structure decreases and structure enters the plastic phase, which is consistent with the conclusion of expansion's uniformity. The metal surface coverage is up to 0.45, and its value is small, which shows that the hinge lozenge grid structure possesses the advantages of small volume and lightweight.

However, there is an opposite tendency in the axial expansion rate. With the pressure increasing, the axial expansion rate climbs gradually. It shows that the hinge lozenge grid structure extends along the axial direction. This phenomenon illustrates that the structure can not only enlarges stent radius, but also extends the stent length, which possesses the feature of "full-scale expansion".

The load, has a significant effect on the springback rate of stent, decreases rapidly after expanding, which indicates the large the plastic strain of the stent. According to the theory of metal plastic deformation and work hardening, the plastic deformation of the structure in the residual stress in the stent and the yield stress increase when the stent is re-expanded. This result, coming out after the proportion of elastic deformation, as well as rebound rate are increasing. At the same time, because the hinge lozenge grid structure is a typical symmetrical structure and possesses a special all direction elongation, it will appear elongation phenomenon after being loaded with the external pressure.

In order to further analyse the full-scale expansion of the hinge lozenge grid structure in expansion process, two points (named Middle Point and Edge Point) in the middle part and edge of stent are selected to survey the variation of X, Y, Z displacement and Von Mises Stress of two parts under different pressures. The pressure with 20 000 Pa, 25 000 Pa, 30 000 Pa, 35 000 Pa and 40 000 Pa are used to numerical analysis by COMSOL Multiphysics. The displacement results along Y-direction are shown in Figure 5.



(a) Middle point displacement along y axis

(b) Edge point displacement along y axis

Figure 5. Middle point and edge point displacement along y axis.

The middle part and edge displacement along y axis can be approximately divided into two stages as shown in Figure 5(a). Stage I, where the compression displacement is up to its summits, the displacement increases rapidly with the force(Figure 5(a) and (b)). Subsequently at stage II, where a displacement decline slowly with the force , the maps show that the structures are bent into plastic range whereas the panels still undergo negligible plastic deformation. Therefore the assumption of rigid folding is satisfied, and the structure can be essentially considered as a mechanism with plastic strain. And displacement deformation with the force along X and Z axis are basically the same with the displacement along y axis. But the maximum displacement in X direction is 0.115 mm, in Y direction is 0.222 mm and in Z direction is 0.0357 mm under the same pressure of 40 000 Pa. So, the displacement value in Y direction is about two times more than that in X direction and about six times in Z direction.

The displacement along X and Z directions are similar. And the material, unit cell thickness, area coverage and diameter are the same, the displacement under 20 000Pa is twice as much as that under 40 000Pa, which indicates that hinge lozenge grid stent has a significant effect on improving the radial support performance. When the stent's pressure exceeds 25 000 Pa, obvious displacement occurs after unloading, and the expansion capability of the edge and middle parts is notable.

Figure 6 represents the stress variation of a hinge lozenge grid structure under external loading. With the increase of external load, the stress increases gradually. Since the initial yield stress in material parameter setting is 207MPa, it can be seen in the figure 6 that when the pressure is greater than 25 000Pa, the material has entered the plastic phase. It also explains the variation of displacement in Figure 5.

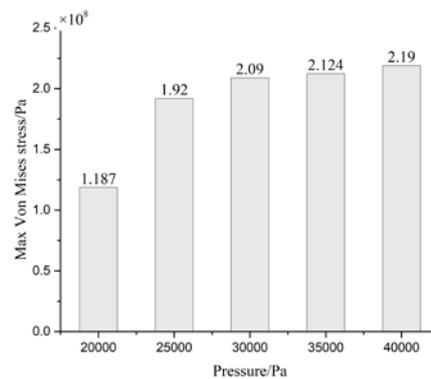


Figure 6. Maximum Von Mises stress.

4. Conclusions

The procession of stent's expansion under different loads are simulated to analyze the expansion, axial expansion ratio and resilience rate of stent aiming to radial support performance and bidirectional expansion of hinge lozenge grid stent, and there exist large deformation and "full-scale expansion" in inflated stents. The conclusions are as follows:

- (1) The hinge lozenge grid stent has a good symmetry of structural deformation in both integral and local and exhibits "full-scale expansion" structural properties under external loads.
- (2) With the expansion of the stent, the springback rate and maximum stress increase, and the diameter of stent is twice as much as initial after expansion.
- (3) Hinge lozenge grid stent is a folded structure with super-large pore, so the axial expansion ratio increases after loading.
- (4) When other conditions remain unchanged, the displacement changes obviously with the increase of pressure.

Based on the above research, It not only improves the radial support performance of intravascular stents significantly, but also overcomes the shortage of traditional stents by applying hinge lozenge grid structure to intravascular stent, which provides a new idea for the design and optimization of intravascular stents.

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