Medical Engineering and Physics 74 (2019) 162–165

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

A finite element simulation method to evaluate the crimpability of curved stents

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ARTICLE INFO

Article history:
Received 9 April 2019
Revised 15 May 2019
Accepted 28 July 2019

Keywords:
Curved stent
Crimpability
Finite element analysis
Curved crimper

ABSTRACT

Stenting of curved arteries is more challenging than straight vessels. There has been an increasing need for new techniques to treat lesions in highly curved locations. One generic idea is to use curved stents to treat lesions in such curved locations. Computational modeling of straight stent crimping which is being used to evaluate the structural performance of the stents has been done vastly in the past. However, there has not been much simulation work on crimping of curved stents due to the challenges associated with applying the boundary conditions. Here we propose a new method to crimp a curved stent to a smaller diameter by incorporating a simple algorithm to generate the required boundary conditions supplementing the finite element (FE) code. To achieve this, a curved crimper is modeled and used to apply crimping loading on the curved stent evaluate its crimpability. Our method provides a simple yet very useful tool which can be implemented in finite element packages to simulate crimping of curved stents using curved crimpers. This method can also be used to expand balloon expandable stents by inflating curved balloons.

1. Introduction

Obstruction due to plaques typically develops at the angled portions of the vascular pathway like arches and bifurcations [1]. Stenting has proven to be an attractive and effective option for treating such lesions [2]. Most of the currently available stents that are commonly used for treating vascular diseases, have a straight configuration. Consequently, there is lack of conformability to the vessel wall when deployed at curved lesions [3]. This is because any vessel curve ranging from 30° to 150°, particularly an acute vessel curve like the one seen in the carotid siphon, requires the stent to adapt to the vasculature with foreshortening at the concavity causing the inward prolapse of the stent struts [4]. Hence there has been a quest for curved stents to treat lesions in highly curved locations [5] like arches and bifurcations so that the stent conforms well to the blood vessel.

Stent crimpability is a crucial factor to consider during the development of nitinol based self-expandable vascular stents [6,7], as mechanical failure of the stent during crimping will lead to serious complications such as metal fracture leading to device failure thereby rendering the stenting procedure unsuccessful. The stent crimping simulation is a non-linear quasi-static problem involving complex contact conditions [8]. Crimping of nitinol based stents has been studied extensively [7,9–15] in the past but most of the crimpability studies have been done on straight stents with a straight rigid cylinder mimicking the crimper. In those studies, the nodes on the straight crimper were constrained axially and circumferentially on a cylindrical coordinate system along the longitudinal axis of the stent. Boundary conditions are then applied to radially contract the crimper thereby compressing the stent to the desired diameter (OD). But to crimp a curved stent we need a curved crimper in which the boundary conditions cannot be easily handled using the existing coordinate systems (i e; Cartesian, cylindrical and spherical) available in the finite element software packages due to the fact that the centerline of the stent is curved. In such a scenario it is required to load the curved crimper in such a way that the applied load radially contracts the curved crimper. Hence in this work, we propose a method which can be implemented in most of finite element packages when crimping a curved stent using a curved crimper.

2. Materials and methods

2.1. Geometry models and material property

The design of the curved stent was based on our previously published work [16]. The curved stent has the same specifications as reported earlier but with a suspended arc angle of 60°.

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https://doi.org/10.1016/j.medengphy.2019.07.017

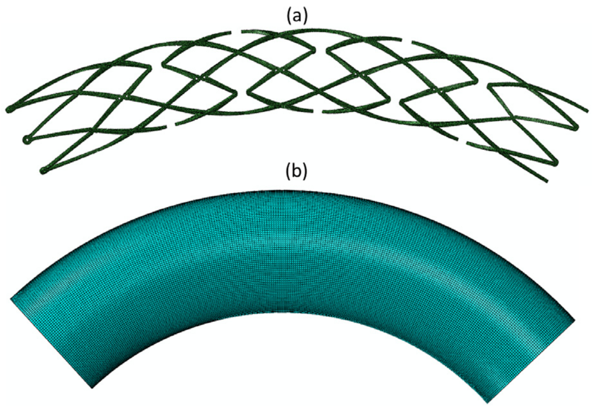

Fig. 1. (a) Finite element model of the curved stent; (b) Finite element model of the curved crimper.

The geometrical model of the bent stent was generated using SOLIDWORKS (Dassault Systemes, Waltham, MA, USA) and imported into ABAQUS (Dassault Systemes) for analysis. The finite element model of the curved stent is shown in Fig. 1(a). The stent was modeled with the C3D8R element. A rigid curved cylinder was designed with a suspended arc angle of 60° which mimics the crimper used to compress the stent. The CAD model of the curved crimper is shown in Fig. 1(b). The curved crimper was meshed with the 4-node quadrilateral surface element (SFM3D4).

Nitinol is the most popular material to develop self-expandable stents owing to its superelasticity, shape memory and remarkable biocompatibility, corrosion resistance, fatigue resistance and strength [14,17,18]. A constitutive model that simulates the superelastic plastic behavior of nitinol was used in this study to represent the stent material. This thermo-mechanical coupled superelastic plastic model [19,20] is implemented by an in-built UMAT for ABAQUS/Standard finite element solver.

2.2. Boundary and loading conditions

The curved stent was assembled inside the curved crimper (see Fig. 2) in the Cartesian coordinate system unlike a straight stent which is typically assembled in the cylindrical coordinate system. We used a surface-to-surface algorithm to model the interactions between the crimper and the stent where a friction of 0.05 was used for the interaction between the inner surface of the crimper and the outer surface of the stent.

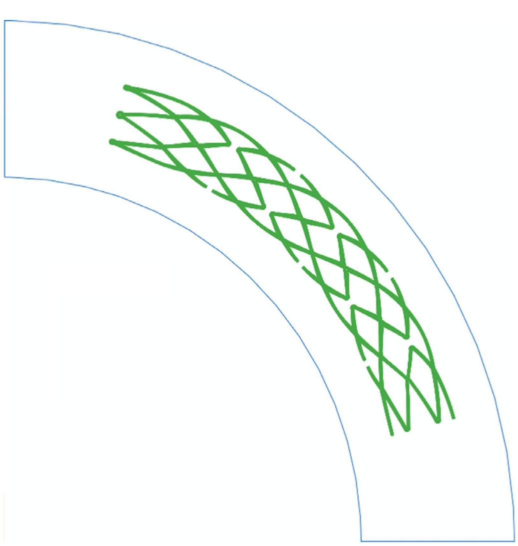

Fig. 2. The curved stent assembled inside the curved crimper.

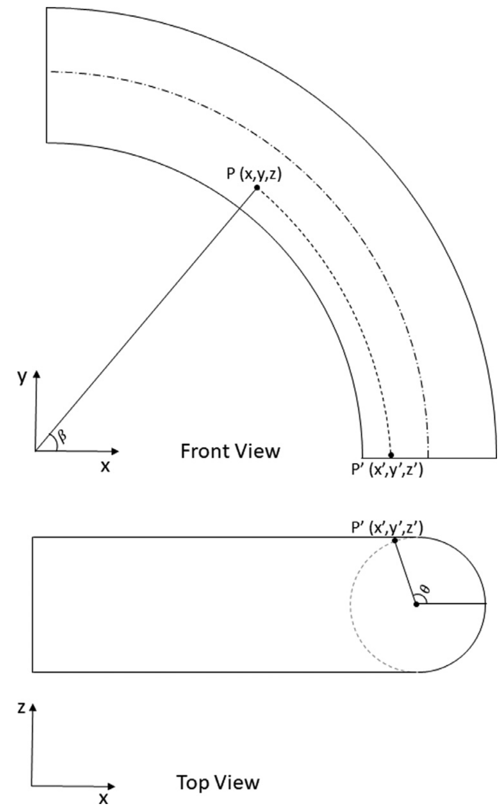

Fig. 3. The schematic of the transformation of the curved stent nodes.

The crimping of the stent is carried out by applying radial displacement on the nodes towards the center line of the stent. For the nodes (see Fig. 3) in the *xz* planes (ie, the nodes at the end of stent) the radial displacement is generated by applying the displacements ($u\cos\theta$, 0, $u\sin\theta$). For all the other nodes of the crimper, the radial displacements were accomplished by transformations. Considering any general node in a given location on the stent denoted by P(x, y, z), rotating P such that it lies on the xz plane leads to a new point which can be termed as $P'(x', y', z')$. From P', we can calculate the radial displacements and translate the displacement vector back to the point P by rotating it about the origin. The above process can be implemented through the following algorithm. Here the center point of the curved crimper is assumed to be in the origin of the Cartesian coordinate system. But this can be generalized with appropriate modification in the algorithm.

Algorithm:

- Consider the node which lies on the point $P(x, y, z)$ and calculate the angle β using the trigonometrical ratio where β is the angle made by the position vector of the point P with the xz plane measured at the origin.
- Rotate the point $P(x, y, z)$ about the origin to obtain $P'(x', y', z')$ so that P'lies in the xz plane using the following transformation matrix:

$$\begin{Bmatrix} x' \\ y' \\ z' \end{Bmatrix} = \begin{bmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix}$$

Here it should be noted that $y' = 0$ due to the fact that P'lies in the xz plane and $z' = z$ as the rotation is about the z axis.

- Calculate the angle θ using the trigonometrical ratio where θ is the angle made by the position vector of the point P' with the x axis in the xz plane.
- Calculate the radial displacement components of P' using the following equations

$$u_1' = r_d \cos\theta$$

$$u_2' = 0$$

$$u_3' = r_d \sin\theta$$

- Translate the displacement components of P' back to P using the following transformation matrix:

$$\begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} u_1' \\ u_2' \\ u_3' \end{Bmatrix}$$

This transformation methodology is repeated for all the nodes in the stent model and thus the radial crimping boundary condition is obtained. This algorithm was implemented using a DISP subroutine in Abaqus.

3. Results and discussion

Figure 4 shows the results of this work. The curved stent is compressed (see Fig. 4a) from an initial outer diameter of 6 mm to 4 mm by the curved crimper. Our crimping load generating algorithm is used to compress the curved crimper from a bigger diameter to a smaller diameter as shown in Fig. 4b. This way we can compress any curved stent to a smaller OD as shown in Fig 4c. The final crimped curved stent crimped stent is shown in Fig. 4d.

It should be noted than any stent (whether straight or curved) will be physically crimped using a standard stent crimping technology. The stent would then be mounted on the delivery system and deployed at the target location. But simulation of a pre-curved stent using a straight rigid crimper will have the following challenges. To apply radial loads for stent crimping we need a cylindrical coordinate system whose 'Z' axis is along the longitudinal axis of the stent. But while modeling a pre-curved stent it will not be feasible to have a coordinate system with 'Z' axis along the stent longitudinal axis as the stent is not straight as published in the literature. Crimping a pre-curved stent using a straight crimper will give rise to numerical instabilities due to sharp contact between the straight stent face and curved stent edges.

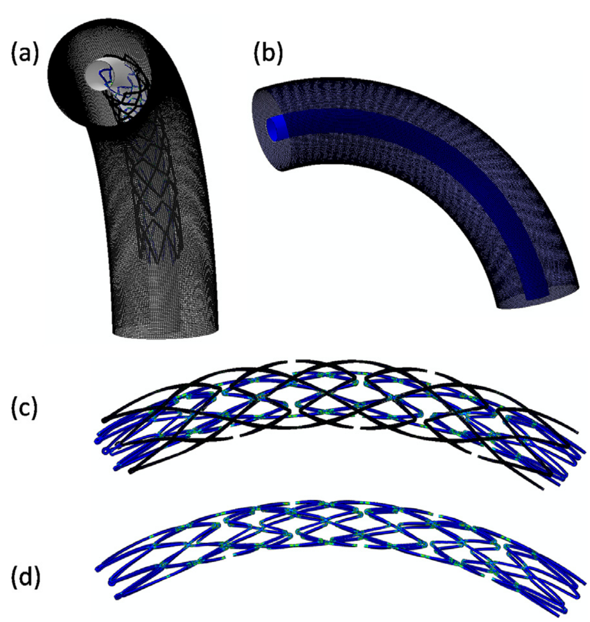

Fig. 4. (a) the deformed configuration superimposed over the undeformed configuration; (b) the deformed crimper superimposed over the undeformed crimper; (c) the deformed curved stent superimposed over the undeformed curved stent; (d) the final crimped curved stent configuration.

Straight stent crimping has been studied extensively in the past by defining an ad hoc local cylindrical coordinate system [8,21–23] at the stent ends to fix the corresponding nodes in the longitudinal and in the circumferential direction consequently allowing only radial displacement. As pointed out earlier, it will not be feasible to use cylindrical coordinate system to compress a curved stent because the center line of the curved stent is not straight as required in a cylindrical coordinate system while applying boundary conditions. One way to overcome this address this challenge is to model the curved stent and the curved crimper in a local toroidal coordinate system. Toroidal coordinates are constructed by three-dimensionalizing the two-dimensional bipolar coordinate system by means of a rotation about the axis that separates its two foci [24]. Toroidal coordinate system has been used for stent expansion in curved vessel [25].

The major challenge in using a toroidal local coordinate system is that it is not available in most of the finite element packages. Hence in this work, we have proposed a simple methodology to apply the boundary conditions which can be implemented in most of finite element packages while crimping a curved stent using a curved crimper. This methodology can also be used for simulation of expansion of curved balloon expandable stents using a curved balloon similar to a previous experimental study [1].

Summary

In a conclusion, this three-dimensional FEM loading model provides a methodology which can be implemented in finite element packages to simulate crimping of a curved stent using a curved crimper. Most of the simulation work done so far has been either on crimping or deployment of a straight stent in a straight artery or a straight stent in a curved artery. On the contrary we have proposed a mathematical method to crimp a pre-curved stent using a curved crimper which has not been reported before to the best of the authors' knowledge. The current work is on simulation of the crimping process alone and we are carrying out realistic simulation of the deployment of a pre-curved stent in a curved artery which will be the progression of the current work. This model can also be used to expand balloon expandable stents by inflating curved balloon.

Declaration of Competing Interest

None.

Ethical approval

Not required.

Funding

This research is supported by the Singapore-China Joint Research Programme (grant no: 1610500025).

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