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Dynamic Analysis of Boron Nitride Nanotube Reinforced Nano Composite Coronary Stents

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Abstract **-Stents are used in angioplasty to support the weak arteries and avoid heart blockages. Boron Nitride Nanotubes (BNNT) reinforced nanocomposite coronary stents are proposed in the paper. The purpose is to increase the design life of the Coronary stents in order to avoid re-angioplasty and the possibility of the clot forming tendency of blood. Composite made coronary stents are modeled and simulations carried out using finite element method. The effects of various stresses acted upon by the arteries, depositions inside the arteries, blood flow conditions and other hemodynamic parameters are studied. . The modal analysis of blood flow system is carried out in order to ensure laminar blood flow and reduce the vascular resistance BNNT Reinforced Composite stents provide longer design life, better biocompatibility and anti thrombogenicity for the stent embedded arteries over the presently used steel coated stents.**

Keywords**:** BNNT, Nano Composites, Stents, Biocompatibility, Modal analysis

1. INTRODUCTION

Engineered Nanomaterial Composites have immense potential in coronary applications due to their biocompatible nature (Kumar et al., 2013, 2014; Singhal et al., 2012, 2013). Boron nitride nanotubes (BNNTs) attract wide biomedical applications due to their unique properties physical properties. BNNT reinforced Nanocomposites are engineered materials with high levels of biocompatibility which make them suitable for coronary treatments. Blockages of the arteries due to the depositions of plaques and collapse of arteries are the prevalent coronary diseases. A stent is a small mesh tube that's used to treat narrow blocked or weak arteries. Stent is placed in an artery as part of angioplasty procedure that can support arterial walls and reduce the risk of heart attack. Currently used metal and metal alloy stents have the possibility of thrombogenicity i.e. the tendency of a material in contact with the blood to produce a thrombus or clot or of blood. Use also leads to restenosis i.e. reoccurrence of the narrowing of blood vessels. Due to their cytocompatibility i.e. compatibility with cells, BNNT reinforced Hydroxy Apatite (HA) nanocomposite stents are proposed in the paper. The purpose of the composite model is to avoid the possibility of thrombogenicity and restenosis. The Finite Element Analysis based study of force interactions of the stents with the arteries and blood flow is done in order provide a analysis support as a pre-clinical testing methodology for estimating the cardiovascular attributes.

2. LITERATURE REVIEW

A boron nitride nanotube can be imagined as a rolled up hexagonal BN layer or as a carbon nanotube in which alternating B and N atoms entirely substitute for C atoms. Most of the researches about BNNTs in bio-application focus on the exploitation of using BNNTs as smart and selective nanocarriers or composition used to reinforce matrix. (Xiaoming Li, 2013). BNNTs are intriguing nanomaterials with a wide range of potential biomedical applications. The assessment of BNNT interactions with biological systems, at both the cellular and sub cellular levels is an essential starting point for determining their bio-safety. The effects of increasing concentrations of BNNTs on human vein endothelial cells were studied and no significant changes were observed in cell viability, cytoskeleton integrity or DNA damage (Serena Del Turcoa, 2013). Hydroxyapatite (HA) has been successfully utilized in orthopaedic surgery for promoting fast fixation of bony tissues owing to its similarity in chemistry to human skeletal bone. Their biocompatibility implies the possibilities of it being potentially used as additives for HA based composites with enhanced mechanical properties (Yi Liu, 2013). BNNT reinforced aluminum based composites were synthesized by spark plasma sintering and the concentration of BNNT is varied as 0.2 and 5 volume % in the aluminum matrix. Micro- pillar compression testing revealed that Al–5 volume % BNNT has yield strength and compressive strength as 88MPa and 216MPa respectively, which is more than 50% improvement over unreinforced Al. (Debrupa Lahiri, 2013)

Stenting has less complications and more recovery chances giving its preferences over open heart surgeries.The use of coronary stents in interventional procedures has rapidly increased from 10% in 1994 to over 80% in current practice. This demands the detailed analysis of stents which is done using Finite Element methods. (Lim D, 2008). Very less work has been done on the interaction of the arteries and the stent.The factors such as the balloon-inflation pressures, stent–strut openings and balloon compliance can influence the contact stresses between the balloon and the arterial tissue within the stent–struts and hence cause vessel injury. Their study was limited to a 2D analysis and furthermore used linear elastic material properties to model the arterial tissue. (C. Lallya, 2005).

3. ADOPTED METHODOLOGY

Dynamic analysis needs the geometrical and material properties of the stents as well as the arteries. The proposed nanocomposite properties, geometry of the model and nonlinear modeling of the arteries are discussed. SOLIDWORKS software is used for the purpose of modeling and ABAQUS is used for FEM analysis.

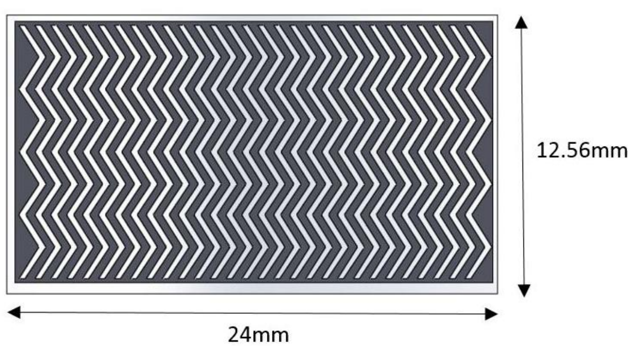
3.1 Nanocomposite Proposed

Hydroxyapatite (HA) possesses chemical composition ($Ca_{10}(PO_4)_6(OH)_2$).Researchers have successfully used Nano crystalline HA for the improvement of mechanical property without having negative effect on its biocompatibility. Ha- 4% BNNT composite have minimal lattice mismatch between HA and BNNT which leads to coherent bonding and strong interface. Composite offers excellent mechanical properties of 120 % increment in young's modulus, 129 % higher hardness and 86% more fracture toughness, as compared to HA. Elastic modulus values, calculated from the unloading part of the load–displacement curves possess higher value of 205+-15 GPa for HA–BNNT. (Debrupa Lahiria, 2010).The Composite rule of mixture for direction parallel to the fibers is applied for Et=750 to 1200GPa, Em =168GPa and f= 4% the material property of composite Ec is predicted as 198 GPa and Poisson's ratio is 0.27. The density of the composite is 7.8g/cc.

$$Ec = (f)Et + (1 - f)Em \qquad f = \frac{Vt}{Vt + Vm}$$

Et : Young's modulus of BNNTs
Em: Young's modulus of Hydroxy apatite matrix
f: Volume fraction of the BNNTs

3.2 Description of Geometry



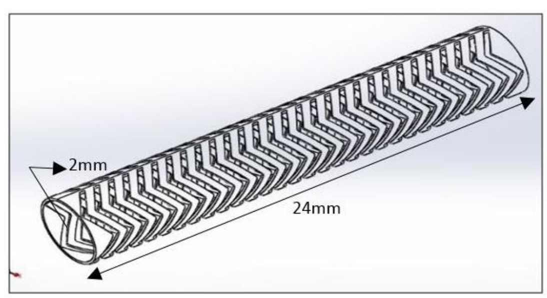


Figure 1 Geometry of Nanocomposite sheet

Figure 2 Stent Model

A model of the stent is made in order to investigate the mechanical behavior of the stents, how it works and how its geometry is made. Stents can be made from sheet, round or flat wire or tubing. The vast majority of coronary stents are produced by laser cutting from tubing as it is one of the easiest manufacturing technique and slotted stent type designs are known for excellent radial strength. The nanocomposite sheet of 0.14mm thickness and 24mm length is bent and joined to form a metallic tubular structure of diameter 4mm as shown in the (figure 2). Peak to Peak pattern is used to design the stent as shown in the figures above. The solid model generated is of the stent in a planar state of geometry if it was cut open longitudinally and flattened out.

3.3 Mesh Generation:

The SOLIDWORKS stent model has then been imported and meshed in ABAQUS.The process of meshing the stent with its complex geometry is done by partition technique with 8632 tetrahedron elements. The cross section of meshed stent is as shown below (figure 3).

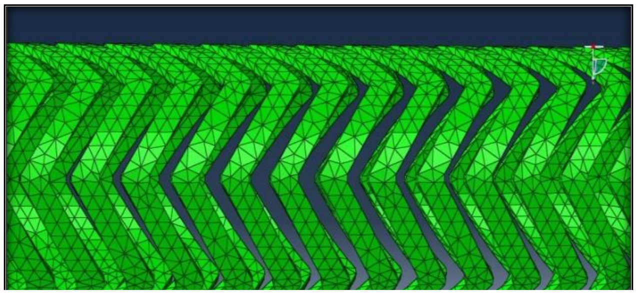


Figure 3 Tetrahedron meshing

3.4 Modelling of Vessel:

Arteries are blocked or narrowed due to the circumferential depositions called as plaque. The high stress in this plaque component may lead to tissue failure and to an increased risk of thrombus formation. Hence stresses caused by plaque along with arteries plays an important role in stent analysis.The two materials of the artery wall, arterial tissue and stenotic plaque, are modelled using a 5-parameter third-order Mooney–Rivlin hyperelastic constitutive equation. This has been found to adequately describe the non-linear stress-strain relationship of elastic arterial tissue. The general polynomial form of the strain energy density function in terms of the strain invariants, given for an isotropic hyper elastic material is

$$W = a_{10} (I_1 -3) + a_{01} (I_2 -3) + a_{20} (I_1 -3)^2 + a_{11} (I_1 – 3) (I_2 – 3) + a_{30} (I_1 – 3)^3$$

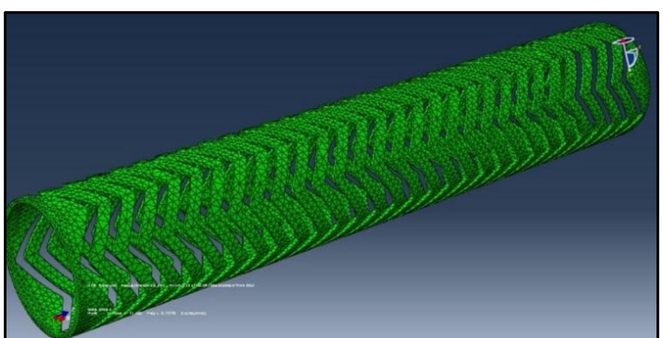


Figure 4 Meshing of entire model

Where W is the strain-energy density function of the hype elastic material, I_1, I_2 and I_3 are the strain invariants and a_{ij} are the hyperelastic constants. (N. Eshghi, 2013)

Table 1: Coefficients of the hyperelastic model

Material	ρ (kg/mm3)	a_{10}	a_{01}	a_{20}	a_{11}	a_{30}
Artery Wall (KPa)	1.066 *10-6	18.90	2.75	85.72	590.43	0
Plaque (KPa)	1.45 *10-6	495.90	506.61	1193.53	3637.80	4737.25

3.5 Loading and boundary conditions:

The stents are placed in the arterial vessels with a flexible tube with a balloon on the end and is threaded through a blood vessel to the narrow or blocked coronary artery. Once in place the balloon is inflated to compress the plaque against the wall of the artery which restores blood flow. The mechanical stresses are produced in the arteries during the expansion. The arteries thus impose radially compressive stresses on the stents. The values of these stresses are 0 to 0.4 MPa. The study of blood flow dynamics is very complex because many mechanical and geometric characteristics are involved. To simplify the model the artery is assumed to be a rigid cylindrical tube in which the flow is laminar Newtonian. Also the blood flow pressure in the arteries is taken as 100mm Hg or 13.3 KPa.
For better accuracy of FEA analysis the arteries pressure and blood flow pressure are applied in 2 steps:
Step 1: The compressive stresses by the arteries and stenotic plaques depositions are applied
Step 2: Keeping the arterial pressure constant the internal pressure due to the blood flow of 100mmHg is applied.

4. RESULTS AND DISCUSSION

4.1 Stress distribution:

The stress interactions between the arteries and the stent or stent edges damage the vessel walls. The aim of this study is to find the stress distribution across the nanocomposite stent. The Von Mises stresses after the analysis are shown below. The stresses induced are below the maximum stresses that will damage the vessel walls. The stent deformation is shown in the figure 5.

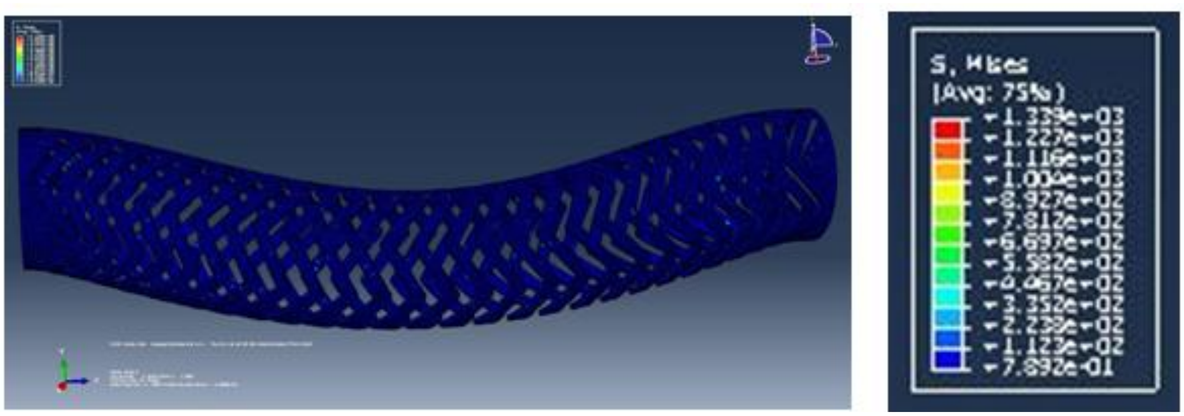


Figure 5 Von Mises Stresses

4.2 Modal analysis:

The modal analysis of the stents is carried out in order to predict the wave speed dispersion for different modes of propagation to estimate elastic properties of these structures along with the vessels and their interaction with the vessel. Modal analysis is also carried out in order to ensure laminar blood flow and reduce the vascular resistance offered to the blow by the stents, the response of the structure is shown in the figure below for different frequencies. For first frequency shape of deformation is a bending motion while second the shape of deformation is a twisting motion. 3rd the shape of deformation is another twisting motion while 4th the shape of deformation is a twisting motion and further is depicted in the figure 6.

	1	2	3	4	5	6
Cycles/time	0.81318	1.0754	1.8696	2.2757	2.514	3.0537
Mode value	26.105	45.65	137.41	204.45	249.64	369.35

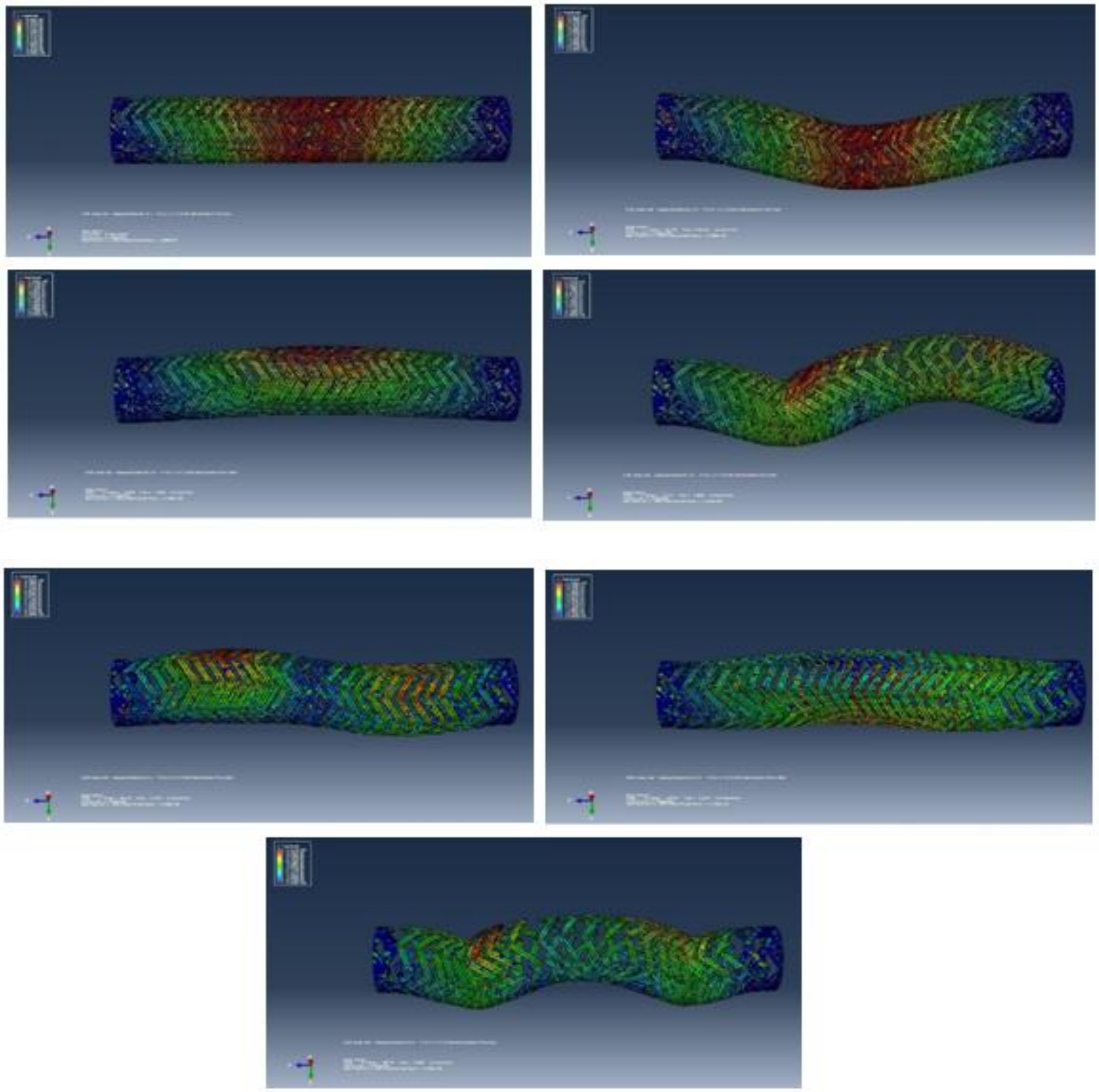


Figure 6 Modal Analysis of the stents

5. CONCLUSIONS

The dynamic analysis of the biocompatible nanocomposite stents was successfully carried out using finite element approach. It shows that the maximum stresses produced in the stent have less potential to induce damages in the vessel walls. The technique also proposes that the stent material properties can be optimized before the surgery in order to avoid damage to the arteries at the maximum stress points.

The different deformation shapes obtained from modal analysis of the stent will further help to predict the modal analysis of arteries along with stents to study the blood flow conditions and other hemodynamic parameters.

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