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Numerical Analysis of Coronary Stent for Diverse Materials

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***Abstract*— Coronary stent implantation is one of the most important procedures to treating coronary artery disease such atherosclerosis. Due to its efficiency, flexibility and simplicity, the use of coronary stents procedures has increased rapidly. In order to have better output of stent implantation, it is needed to analyze the biomechanical behavior of this device before manufacturing and utilizing. Finite element method is one of the most effective methods to investigate biomechanical behavior of the stent. The objective of this research work is to investigate expansion characteristics of coronary stent for diverse materials, such as PEEK 450G, Magnesium AZ31 and Cobalt-Chromium L605. The results demonstrate the radial displacement, dogbone ratio, foreshortening, and flexibility of diverse materials.**

Keywords: Atherosclerosis, Stent, Cytotoxicity, Biocompatibility, Finite element method

I. INTRODUCTION

Coronary Artery Disease (CAD) is the most common cause of death in the world, accounting for 48% of all deaths in the world. Coronary artery disease, also known as atherosclerosis occurs when excess cholesterol attaches itself to the walls of blood vessels as shown in fig1. Embedded cholesterol also attracts cellular waste products, calcium and fibrin. This leads to a thickening of the vessel wall by complex interaction with constituents of the artery. The resulting pasty build-up known as plaque can narrow or even block the arteries that obstruct the flow of oxygen rich blood [1]. CADs are now a days the leading cause of death in the Western countries: a recent report of American Heart Association states that, on the basis of 2006 mortality rate, nearly 2300 Americans die of CAD each day, an average of 1 death every 38 seconds. This data explains well the high incidence of such pathologies which lead to high social and economical costs; in fact, the estimated direct and indirect cost of CVD for 2010 is $ 503.2 billion [2]. Several procedures are available to revascularise a blocked artery, including balloon angioplasty and stenting, bypass surgery and atherectomy [3]. Fourty years ago, coronary artery bypass surgery (CABG) was the popular revascularization treatment used to treat obstructive coronary artery diseases. However, it was claimed that frequent coronary closures occurred and hence emergency surgical revascularization was necessary [4, 5].

Stenting shows some advantages compared to other possible treatments, as it does not any surgical operation and has less complication, pain and a more rapid recovery. So the use coronary stents in interventional procedures has rapidly increased from 10% in 1994 to over 80% in current practice [6]. In order to have the better output of stent implantation, it is needed to analyze the mechanical behavior of the stent before manufacturing and utilizing. One of the most effective methods to investigate the mechanical behavior of stent is finite element method. In comparison with expensive experiments carried out in hospitals and laboratories, numerical simulations accomplished by computers have advantages in both flexibility and cost [7].

A stent is an expandable tube like device that is inserted in to a natural conduit of the human body to restore a disease induced localized stenosis. The material used for human cardiovascular stent implants are conventional materials, with heavier density, not economical and unstable. It is observed that implant materials are affecting the coronary vessel where the failure of implant is maximum due to wear, corrosion, and fatigue; the above problems are due to improper material selection. From the literature review PEEK450G polymer shows an excellent wear resistance, chemical resistance, mechanical properties, low density material, physically stable, biocompatible and also machinable[8]. Therefore in this intended investigation, low density and stable material such as PEEK450G can be selected for cardiovascular stent implant. And also comparing this material with existing stent materials such as Magnesium AZ31 and Cobalt-Chromium L605.

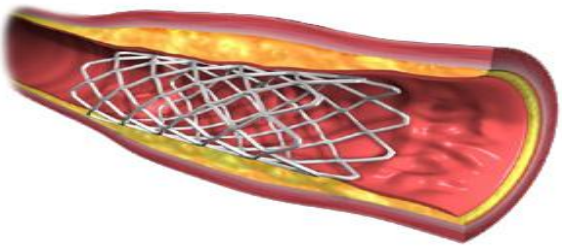


Fig.1 Coronary Stent with Artery

II. MATERIALS AND METHODS

In the present study materials used for coronary stents are PEEK 450G (Polyether-ether ketone) Magnesium AZ31 and Cobalt-Chromium L605 alloy. Primary model of stent was produced by using commercially available software. The model was constructed on the basis of images from literature [9]. The stent has an outer diameter of 1.915mm, length of 15mm and a thickness of 0.05mm. Fig.2 shows the linear array of 5 instances stent model in its unexpanded configuration.

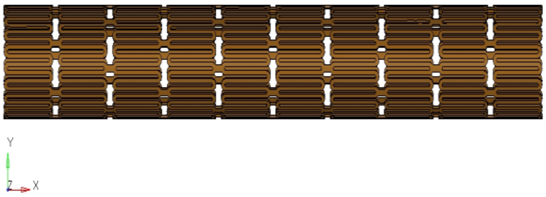


Fig. 2 Linear array of 5 instances stent

III. FINITE ELEMENT ANALYSIS OF STENT

A. *Coronary stent*

The model shown in the fig.2 is exported as IGES file. This file is imported into the HYPERMESH V11 software where the implant model is opened. The 3D finite element model required for analysis is created by discretizing the geometric model as shown in the fig.3; the discretization was performed in HYPERMESH software. The stent modeled by linear 8-noded solid element which is defines as solid C3D8R in abaqus. The finite element model of the stent consisted of 108080 nodes and 40852 elements.

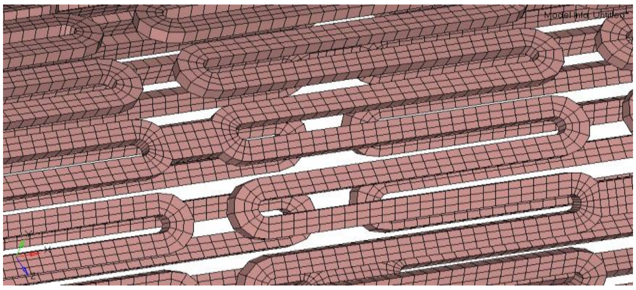


Fig.3 Finite element meshed model of stent

B. *Balloon*

In this step, geometrical representation of balloon design is created based on reference [10]. The balloon as a medium to expand the stent was modeled to be 25mm length. The outer diameter and thickness of the balloon were 1.79mm and 0.05mm, respectively. A nylon material was used to represent the balloon. Similar to the stent model, the balloon was modeled by linear 8-noded membrane element which is defines as membrane M3D8R in abaqus. The finite element model of the stent consisted of 13805 nodes and 13750 elements as shown in fig.4.

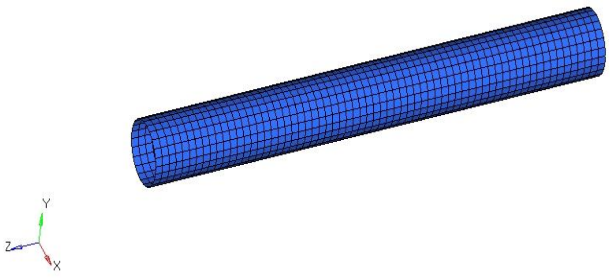


Fig.4 Finite element meshed model of balloon

C. *Material Properties*

The mechanical properties for Co-Cr L605 and Mg AZ31 are found in reference [10]. Table 7.1 gives the mechanical properties of the two alloys. The mechanical properties of PEEK 450G are found in VICTREX® PEEK450G medical document data is considered as per room temperature [11].

TABLE.1 BIO-INERT MATERIAL PROPERTIES [10, 11]

Material	Material Properties			
	Young's Modulus E in (MPa)	*Density ρ in (kg/mm3)*	*Poisson's Ration υ*	*Yield Stress σy in (MPa)*
PEEK 450G	3700	1.30E-06	0.36	100
Magnesium (MgAZ31)	43000	1.70E-06	0.35	164
Cobalt-Chromium (Co-Cr L605)	243000	9.10E-06	0.3	476

D. *Loads and Boundary Conditions*

Left hand side of the balloon is constrained in all DOF, whereas right hand side of the balloon is constrained, but axially free in Z-direction, and pressure applied on the inner surface of the balloon, frictionless contact is defined between balloon and stent it is shown in fig.5.

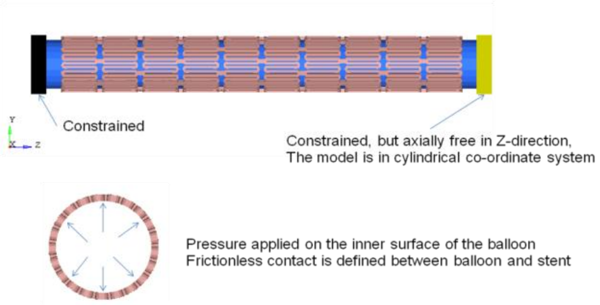
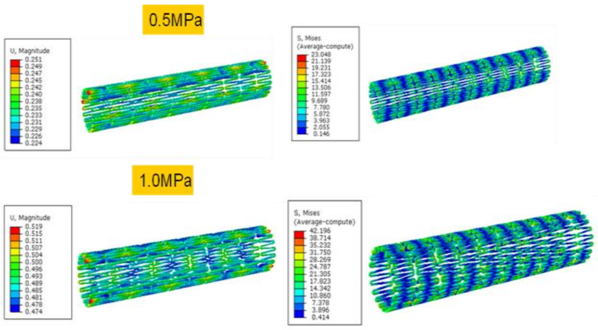


Fig.5 Finite element model of stent and balloon with boundary conditions

IV. RESULTS AND DISCUSSION

A. *Stent Stress Analysis*



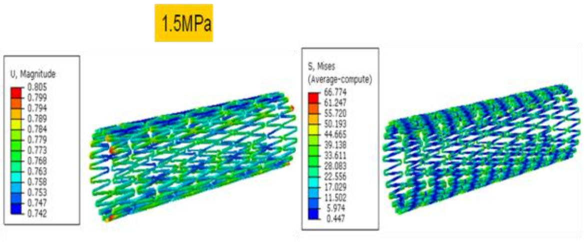


Fig.6 Displacement and stresses for PEEK 450G at different pressure load cases

TABLE.2 DISPLACEMENT FOR PEEK 450G, MG AZ31 AND CO-CR L605 AT DIFFERENT PRESSURE LOAD CASES

Materials	PEEK 450G	Mg AZ31	Co-Cr L605
Pressure load cases MPa	*Displacement (mm)*	*Displacement (mm)*	*Displacement (mm)*
0.5	0.25	0.24	0.15
1.0	0.51	0.5	0.32
1.5	0.8	0.77	0.5

Table.2 Shows radial displacement for PEEK 450G, Magnesium AZ31 and Cobalt-Chromium L605 are 0.8mm, 0.77mm and 0.5mm for different pressure load cases. The radial displacement for PEEK 450G is maximum as compared to the other two materials, it is shown in fig.7. The stresses for PEEK 450G, Magnesium and Cobalt-Chromium are 67MPa, 221MPa and 542MPa as shown in Table.3. The stress generated for PEEK 450G is less as compared with other two materials, as shown in fig.8.

TABLE.3 STRESS FOR PEEK 450G, MG AZ31 AND CO-CR L605 AT DIFFERENT PRESSURE LOAD CASES

Materials	PEEK 450G	Mg AZ31	Co-Cr L605
Pressure load cases MPa	*Stress (MPa)*	*Stress (MPa)*	*Stress (MPa)*
0.5	23	162	477
1.0	42	195	499
1.5	67	221	542

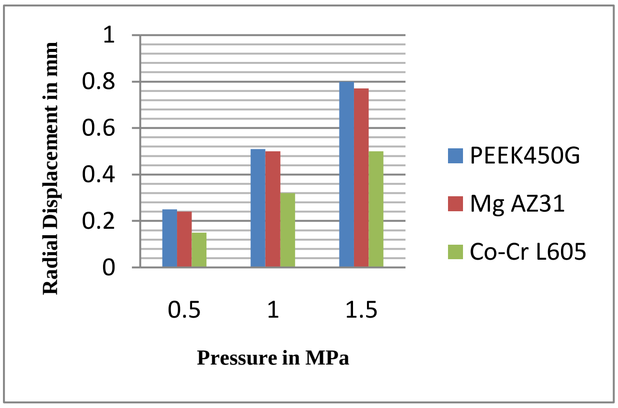


Fig.7 Displacement for PEEK 450G, Mg AZ31 and Co-Cr L605 at different pressure load cases

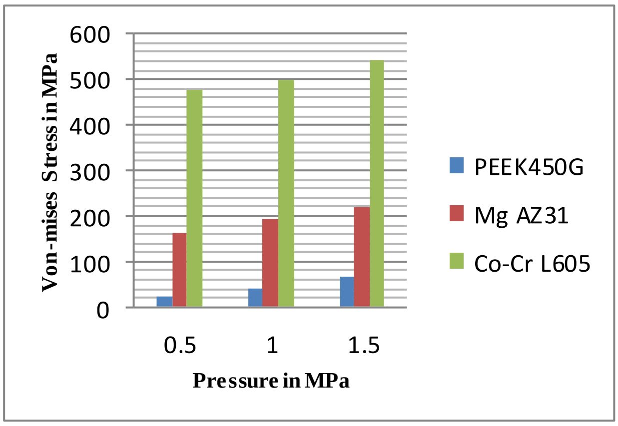


Fig.8 Stress for PEEK 450G, Mg AZ31 and Co-Cr L605 At different pressure load cases

B. Stent Dogbone Ratio

When the stent expands, because of different distribution of circumferential stress between the free ends and the central part, it bends on edges that causes the diameter at the end sides becomes larger than that of the middle of the stent. This phenomenon is called dog boning. According to the findings of the clinical studies, a stent is expected to have the low dog boning. The dog boning is defined as:

$$\text{Dog boning} = \frac{D_{distal}^{load} - D_{central}^{load}}{D_{distal}^{load}}$$

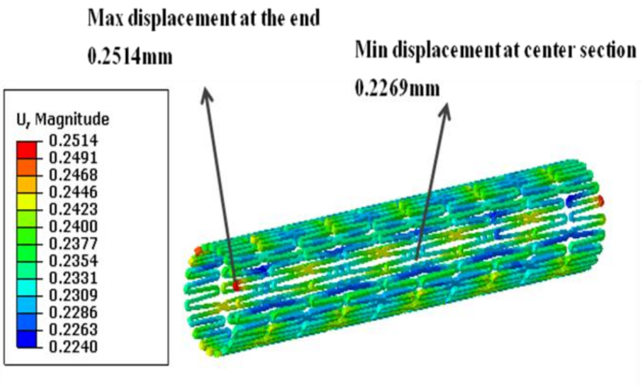


Fig.9 Dogbone ratio for PEEK 450G at 0.5MPa

TABLE.4 DOG BONE RATIO FOR DIFFERENT MATERIALS

Materials/Pressure load cases	Diameter expansion/Dog bone ratio (%)		
	PEEK 450G	Mg AZ31	Co-Cr L605
0.5 MPa	9.75	9.04	14.69
1.0 MPa	8.54	7.52	14.27
1.5 MPa	7.70	3.72	13.14

Table.4 shows the dogbone ratio for PEEK 450G, Magnesium AZ31 and Cobalt-Chromium L605 at different pressure loading cases. The dog bone ratio is 7.70, 3.72, and 13.14% at 1.5MPa pressure loading case. Dog bone ratio for Cobalt-Chromium L605 is maximum as compare to the PEEK 450G and Magnesium AZ31.

C. *Stent Foreshortening*

As mentioned above, because of the dog boning phenomenon, the diameter at the end sides of the stent becomes larger than that of the middle of the stent. This results a reduction in the stent length which is called foreshortening. In fact, foreshortening defines the effective length of the stent and according to the findings of the clinical studies; a stent is expected to have a low value of foreshortening. The foreshortening is defined as:

$$\text{Foreshortening} = \frac{L - L^{load}}{L}$$

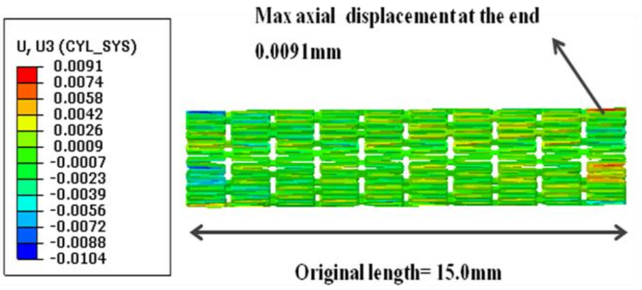


Fig.10 Foreshortening for PEEK 450G at 0.5MPa

TABLE.5 FORESHORTENING FOR DIFFERENT MATERIALS

Materials/Pressure load cases	Foreshortening (%)		
	PEEK 450G	Mg AZ31	Co-Cr L605
0.5 MPa	0.60	0.28	0.19
1.0 MPa	1.18	0.68	0.47
1.5 MPa	1.70	1.67	1.33

Table.5 shows the foreshortening values for PEEK 450G, Magnesium AZ31, and Cobalt-Chromium L605. The foreshortening values are 1.70, 1.67, and 1.33% at 1.5MPa load case. The foreshortening of PEEK 450G is maximum as compare to the other two materials.

D. *Stent Flexibility*

Stent will face swift disturbance due to artery movements for which it is displaced to understand the flexibility of stent, stent is displaced to 0.5mm at the more or less mid section when stent faces swift disturbance we will find stress, displacement and strains at different sections of stent.

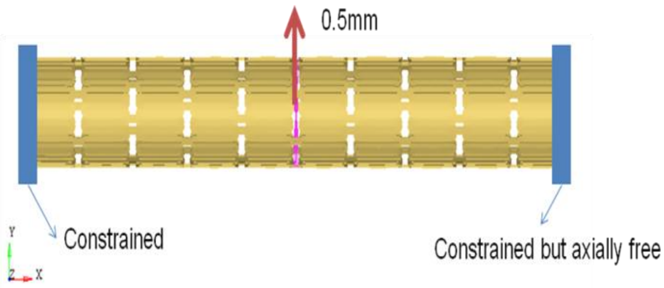


Fig.11 Stent flexibility boundary conditions

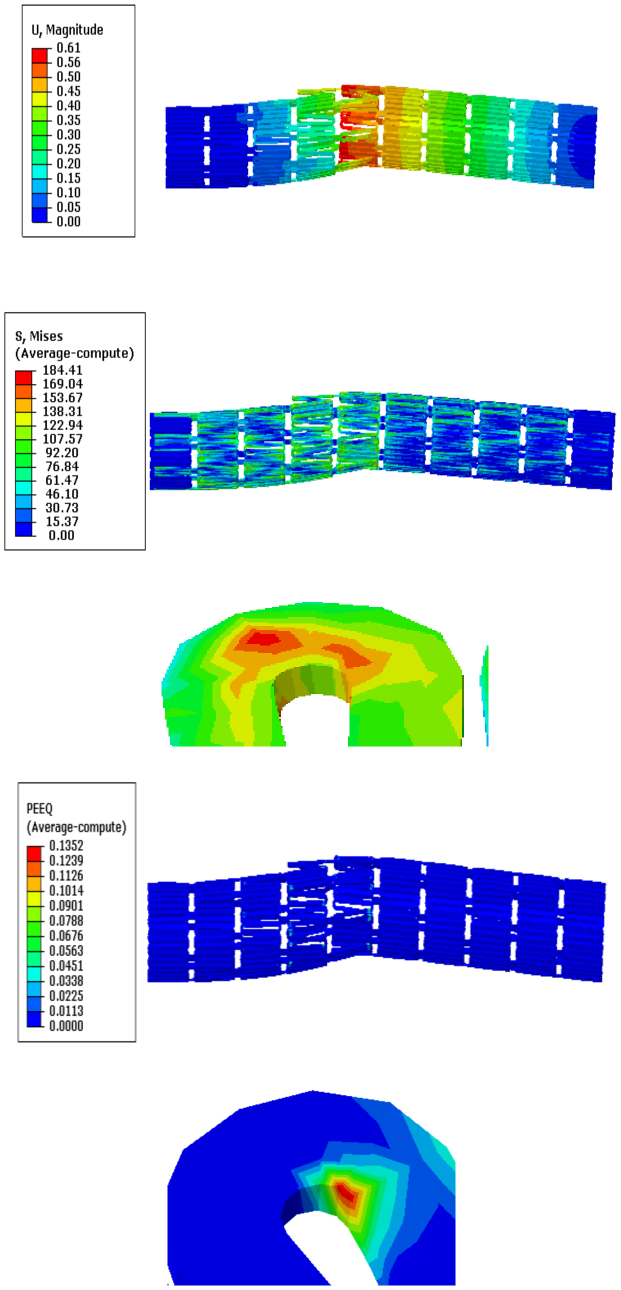


Fig.12 Displacement, Stress and Plastic Strain for PEEK 450G at 0.5mm displacement

TABLE.6 DISPLACEMENT, STRESS AND PLASTIC STRAIN FOR PEEK 450G AT 0.5MM DISPLACEMENT

Materials	Stent flexibility		
	PEEK 450G	*Mg AZ31*	*Co-Cr L605*
Displacement (mm)	0.61	0.55	0.56
Stress (MPa)	184	238	850
PEEQ (%)	13.52	0.8	4.33

The displacement of PEEK 450G, Cobalt-Chromium L605 and Magnesium AZ31 are 0.61mm, 0.56mm and 0.55mm. The displacement of PEEK450G is maximum as compare with other two materials. The stress generated in Cobalt-Chromium L605 is maximum as compare to the PEEK 450G and Magnesium AZ31. Plastic strain is very less in Magnesium AZ31 as shown in table.6.

V. CONCLUSION

Realistic features of materials on the basis of results obtained from Finite Element Analysis, considering the different pressure loads exerted by blood pressure of human body on Stent implants are concluded as follows with respect to displacement, stresses, dogbone ratio, foreshortening and flexibility.

Radial displacement of PEEK 450G is better as compare to the Magnesium AZ31 and Cobalt-Chromium L605, Stress analysis shows PEEK 450G is better material than Mg and Co-Cr with applied pressure load, PEEK 450G does not have plastic strains and stresses are within the yield limits.

Dog bone ratio should reduce with more pressure which is observed in calculations and results are reasonable for all materials, with no plastic strains PEEK 450G is better with dog bone ratio. Foreshortening should increase with more pressure which is observed in calculations and results show more foreshortening for PEEK than the other materials.

A Stent flexibility result shows PEEK450G is more flexible with more displacements for swift changes inside the artery. Finally PEEK 450G is recommended for future coronary Stents.

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