The Effect of Dynamic Loading on Stresses Induced in Charnley Hip Prosthesis

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ABSTRACT

This study produces an image of theoretical and experimental case of high loading stumbling condition for hip prosthesis. Model had been studied namely Charnley. This model was modeled with finite element method by using ANSYS software, the effect of changing the design parameters (head diameter, neck length, neck ratio, stem length) on Charnley design, for stumbling case as impact load where the load reach to (8.7* body weight) for impact duration of 0.005sec.An experimental rig had been constructed to test the hip model, this rig consist of a wood box with a smooth sliding shaft where a load of 1 pound is dropped from three heights. The strain produced by this impact is measured by using rosette strain gauge connected to Wheatstone bridge for the model .The signal is amplified and sent forward to a data acquisition and then saved in the connected laptop. From this study it is found that the changing in stem length had large effect on effective stress where the change in effective stress while stem length increased from (110mm to 140mm) was not more than (209MPa).

Keywords: hip prosthesis; charnley design; finite element method; design parameters; data acquisition

تأثير الحمل الديناميكي على الاجهادات المتولدة في مفصل الورك الصناعي من نوع جارلي

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الخلاصه

هذه الدراسه قدمت تصور نظري وعملي عن حاله حمل عاليه جدا هي حالة التعثرعلى بديل مفصل الورك الصناعي وقد تم دراسة موديل من نوع جارلي.تم تمثيل النموذج بطريقه العناصر المحدده وذلك بواسطة برنامج الانسز للموديل جارلي ودراسه تأثير تغيير المتغيرات التصميميه للموديل جارلي (نصف قطر الكره , طول العنق , نسبة تغيير العنق , طول الجذع) لحالة الحمل الصدمي في حالة التعثر حيث يصل الحمل الى (8.7* وزن الجسم) ولمدة صدمه مقدارها 5 مللي ثانيه.الطريقة العمليه التي تم العمل بها هي صناعة هيكل مستطيل مجوف بداخله ذراع املس ينزلق عليه الحمل من ثلاث ارتفاعات .وتم تحسس الانفعال الناتج من الصدمه بواسطة مقياس انفعال ثلاثي للموديل جارلي حيث تم استخدام قنطرة وتستن ومضخم فولتيه لتتجه الاشاره نحوجهاز حيازة البيانات ومحولها ثم الى الكومبيوتر.وجد ان اكثر المتغيرات التصميميه تأثيرا على الاجهاد المحصل في الجزء الاضعف في موديل جارلي هو طول الجذع حيث ان مقدار التغير في الاجهاد الاعظم عند تغيير طول البديل من (110ملم الى 140ملم) لم يتجاوز (209 ميجاباسكال).

الكلمات الرئيسيه: مفصل الورك الصناعي, تصميم جارلي, طريقة العناصر المحدده، المتغيرات التصميمية، جهازحيازة البيانات.

1. INTRODUCTION

This work presents an overview about the hip joint, the causes of its failure and the historical attempts to overcome this problem as well as the most important stem types used in this field enhanced by some definitions and concepts related to the shape variables and materials. Total hip replacement is most commonly used to treat joint failure caused by osteoarthritis or other diseases. The aims of the procedure are pain relief and improvement in hip function. Hip replacement is usually considered only once other therapies, such as physical therapy and pain medications, have failed. In order to design a successful stem implant some important things must take in account such human activities, weight and age. Some of researchers such as ,H.F. **El'Sheikh, et.al., 2003**, studied a component (hip prosthesis) had been subjected to a dynamic load due to stumbling and the peak static load of the same patient load activity. Two quantitative measures are calculated: peak stress and stressed volume. It has been shown that each measure may lead to differing conclusions. It is concluded that from a thorough analysis of the hip prosthesis components (prosthesis, cement mantle and bone) it is not the peak stress but rather the proportion of the stressed elements (or stressed volume) which should be the indicator if a precise analysis of the load transfer mechanism is required. In static analysis the material was assumed to be linear elastic continuum with isotropic properties, whereas in dynamic analysis it was assumed to be bi-linear elastoplastic, and studied the effect of some design parameter such as stem thickness, the effect of changing the material, the effect of changing the stem length, the effect of collar of hip prosthesis and the effect of damper on stresses induced in prosthesis.

2. FINITE ELEMENT MODEL

The concept of piecewise discretization or dividing a complex object into simpler pieces is one of the oldest logical concepts known to man, when trying either to construct a complex shape or to understand an enigmatic phenomenon. More recently, structural engineers had developed matrix methods for the analysis of framed structures, which can easily be recognized as assemblages of members or, element, connected by joints, or nodes. The finite element (FEM) can now be considered as the most popular theoretical technique ever known to man, and it has been applied successfully to many engineering disciplines, such as structural mechanics, computational fluid dynamics, tribology, heat transfer , electromagnetism, biomechanics,… etc.

The Charnley model which was used should be discretized to small elements for finite element analysis; the element type that used in this discrediting was SOLID45, 10-node tetrahedral. SOLID 45 has a quadratic displacement behavior and is well suited to modeling irregular meshes; the element is defined by 10 nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions as shown in **Fig. 1** , the element has plasticity, , creep, stress stiffening, large deflection, and large strain capabilities with respect to contact region between cup and femoral head the element contact 174 had been used where this is a three- dimensional, eight-node , higher order quadrilateral element that can be located on the surfaces of three- dimensional solid or shell element with mid side nodes, It can be degenerated to 3-7 node quadrilateral triangular shapes, and also element target where it is a three-dimensional element and shape is described by a sequence of triangles, quadrilaterals, straight lines , parabolas, cylinders, cones, (Release 14.0 Documentation for ANSYS 2012).With changing the coarser of this element in order to investigate the right element number. The result of the convergence test show that the best element number that can 253481elements as in **Fig. 2** .

3. MATERIAL PROPERTIES

The material properties of each types of hip prosthesis that are used in present work are illustrated in **Table1, Zafer Senalp , et.al., 2007,** below where the Charnley hip prosthesis is made from (stainless steel alloy 316L)..And acetabulum cup made from ultra-high molecular weight polyethylene (UHMWPE)**, Mamdouh, 2012**.

4. LOADING AND BOUNDARY CONDITION

For dynamic analysis, the load time curve during walking that applied as time history of the dynamic load components for 5 s show that the maximum load applied on hip prosthesis reached to 8.7 times the body weight during stumbling case so the case with this excessive load should be studied, In our study we take stumbling case as impact load with time of impact (impact duration) of (0.005sec), **El'Sheikh, et.al., 2003,**. The boundary condition which had been applied in this work is according to (ISO-7206 standard, modified in 2002) .Where 60% of stem length (which is the distance from stem distal point to center of head ball) was fixed**, Chan-tsungyang, et. al., 2009.** The design parameters that studied is shown in the **Fig. 3** Charnley model.

5. EXPERIMENTAL

5.1 Model to be Tested

In this study real models of total hip prosthesis which had been bought it from market deal with prosthesis (DePuy-Synthes device market).We used Charnly hip prosthesis for this type of total .The dimensions of Charnley hip prosthesis is shown in **Table 2. . Fig. 4** shows the real Charnley model that had been studied.

5.2 Experimental Circuit

The interface circuit which has been used consists of rosette strain gage and whetstone bridge with signal amplifier and this circuit is connected to data acquisition of 16 Flexible I/O (Digital Input, Digital Output, or Analog Input) (LabJack–U3-LV,Colorado,USA) and it is able to read and write the signal in millisecond . This system was linked to a computer for storage and analysis of data using software LabJack UDV3.25computer to record the results with time, the circuit is shown in **Fig. 5**.Where this figure showed the method of circuit connections and its parts.

5.3 Testing Device

The test rig has been designed to simulate the environments of loading case of reference, **Farhad N. et. al., 2008,** where a frame work consists of smooth steel sliding shaft that allows weights to be dropped on the hip prosthesis from different height up to 30 cm ,as shown in **Fig. 6** which shows the test rig and the assisting measuring devices . In the different impact loads had been applied by falling weight of (1pound=453.59g) from 30cm then from 20cm and then from 10cm. A rosette strain gauge (Tokoyo Sokki Kenkyujo co.,LTD. –Japan) attached on the hip prosthesis (Charnley) connected to a Wheatstone bridge with signal amplifier measures the strain and gives the amplified signal from(0 to 4.8 volt) to LabJack data acquisition where a stream UD software gives the final values of strain with the aid of scaled equation of voltage. The final results are compared with those obtained by ANSYS. One of the most important case in experimental part is the fixation of the model during the test because the bad fixation may lead to wrong results and also became a far from reality, the (ISO7206-4 standard, Modified in 2002) solved this problem where by this standard we can become near to the reality case. In this study according to modified ISO7206-4 standard 60% of stem length of hip prosthesis is fixed by using gypsum type 4(elite stone ,thixotropic,zermak-italy) which is used for fixation of master models in removable prosthesis. The fixing stone holds the distal end of the stem starting at 40% from center of the femoral head with stone thickness of 70mm.In addition, the stem is aligned at 10◦ in adduction and 9◦ in flexion, **Chan-tsungyang, et. al.2009,** as shown in **Fig.7** showed the fixation of Charnley type **Tables 4, 5** shows comparison between numerical and experimental results

6. RESULTS

In **Figs. 8, 9** different head and diameter (22mm,26mm) respectively were shown and it is clear from this figure that the position of maximum effective stress for both sizes was the same , where increasing head diameter lead to increase maximum effective stress by (16%), this is due to the shifting of load position which increases the moment on the weakest part. The effective stress for Charnley design with (a) 32mm neck length and (b) 40mm neck length, shown in **Fig. 10,11.** certainly increasing neck length will lead to increase maximum effective stress and that is clear from this figure. Increasing neck length from 32mm to 40mm lead to increase the maximum effective stress by (1.5%) it is small value compared with increasing head diameter or increasing stem length. It should be noted that increasing neck length lead to increase the effective stress at necking section by (32%). The effect of varying two neck ratio ((a) 0.5, (b) 0.8) is shown in **Figs. 12, 13,** respectively, it's clear to be noted that increasing neck ratio is not effected with large amount on maximum effective stress where increasing neck ratio from (0.5 to 0.8) didn't change the maximum effective stress at stem more than (3%), but decreases the effective stress at neck by (28%), this is due to reduction in stress concentration at necking section.

Figs. 14, 15. show the effective stress for Charnley design with stem length (a) 110mm (b) 140 mm, from figure the maximum effective stress is at the same position for both stem sizes with different values where maximum effective stress increased by (16%) with increasing stem length. This is due to the reduction in cross sectional area of the loaded section with increasing stem length.

7. DISCUSSION

Fig. 16 shows the variation of effective stress with respect to changing the head diameter , the relation theme gives indication that with increasing the head diameter the effective stress in weaken part of hip prosthesis will increase and this relation may be caused by the sweeping of load position in vertical direction due to increase the head diameter, this sweeping of load position lead to increase moment at weaken part and thus will increase the stress. The change in effective stress values while head diameter increased from(20mm to 26mm) with step of 2mm was not more than (73Mpa) except head diameter of 22mm where change in effective stress reached to (121Mpa).

Fig. 17 shows the variation of effective stress with changing of neck ratio(neck ratio: represent the position of necking part with respect to total neck length),the chart theme shows that it should take into account while designing to make the neck ratio more than 0.5 as possible to decrease the force arm on neck where this may prevent the fracture at neck and lead to decrease the stress at weaken region of hip prosthesis so it should take into consideration to make balancing of changing this factor and it is clear that changing of stress is not more than (42Mpa) for changing this parameter from (0.5 to 0.8).Except neck ratio of (0.6) where change in effective stress reached to (97MPa).

Fig. 18 shows the variation of effective stress with respect to changing the third design parameter that is the stem length and so due to this point it is clear to most biomedical researchers and (Depuy-synthes) manufacturing companies, that produced medical orthotropic products, to reduce the stem length as possible to prevent the increasing in stress where this increasing in stress may be caused by three reasons the first one is by increasing stem length the overall mass of system with axial axis of hip prosthesis will increase, the second reason is increasing the stem length lead to increase the free part of the fixed hip prosthesis according to (ISO_7204 standard modified in 2002) and that lead to increase the bending stress in weaken part. Second thing is increasing the weight of free part of fixed hip prosthesis. The third reason is increasing stem length lead to decrease the stem cross sectional area to be loaded; this decreasing in stem cross sectional area is due to curvature shape of stem. The change in effective stress while stem length increased from (110mm to 140mm) was not more than (209Mpa) except stem length of (130mm) where change of effective stress reached to nearly (245Mpa)so the stem length of (130mm) and what is nearest to this value should be averted while designing stem.

Fig. 19 shows the variation of effective stress in weaken part of hip prosthesis (at stem) with changing the neck length and it is clear that increasing neck length lead to increase the effective stress due to increase the arm of force where that leads to increase the stress. In this study five sizes of neck length had been used, and it turned out that changing of neck length from(110mm to 140mm) lead to change the effective stress with value more than (53Mpa) except neck length of (36mm),(32mm) where change jumped to (73Mpa).

8. CONCLUSIONS

1. It is found that changing in stem length lead to increase the effective stress with values higher than the other designs parameters so it should be taken in account this parameter because of its heavy influence on effective stress so for Charnley design the stem length should be decreased as possible, under cases of impact load. Changing in effective stress not exceeded (22%).
2. It is found that the changing in head diameter had an influence on effective stress values but with small amount as compared with stem length, where changing in effective stress not exceeded (16%).
3. It is found that the increasing of the neck length for Charnley design lead to increases effective stress with values less than stem length where changing in effective stress not exceeded (5.5%). So that it must be decreased as possible, where increasing neck length lead to increase maximum effective stress.
4. The effect of the ball radius on both contact pressure and total contact stress is larger than that on the effective stress. Where changing in contact pressure not exceeded (41%), and changing in total contact stress not exceeded (32%).
5. It is found that increasing the neck ratio had an effect on the effective stress, where changing in effective stress not exceeded (7%).

6. It is found that the best sizes of low effective stress with these dimensions (head diameter of 22mm, 0.6 neck ratio, stem length of 110mm, neck length of 24mm) can be considered as safest sizes.

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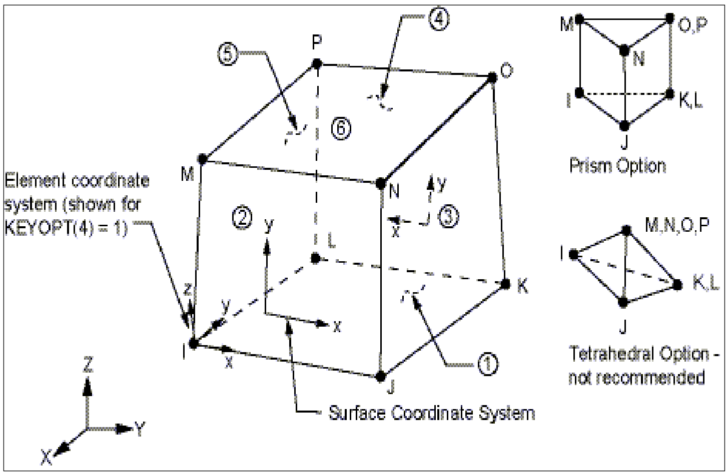

Figure 1. Solid45 geometry.

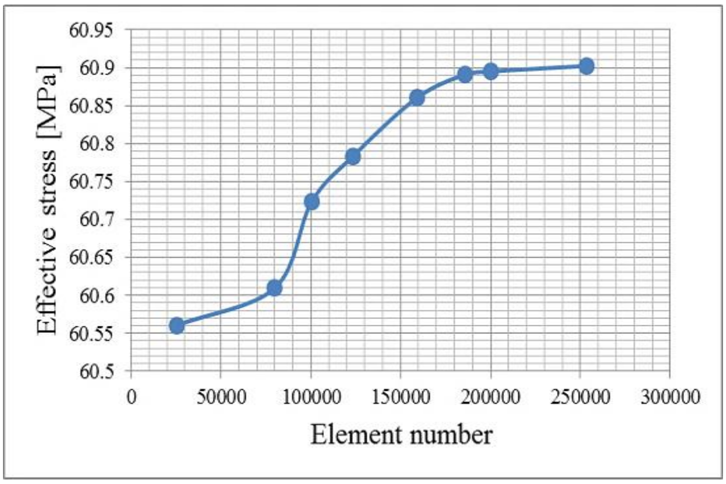

Figure 2. Convergence test.

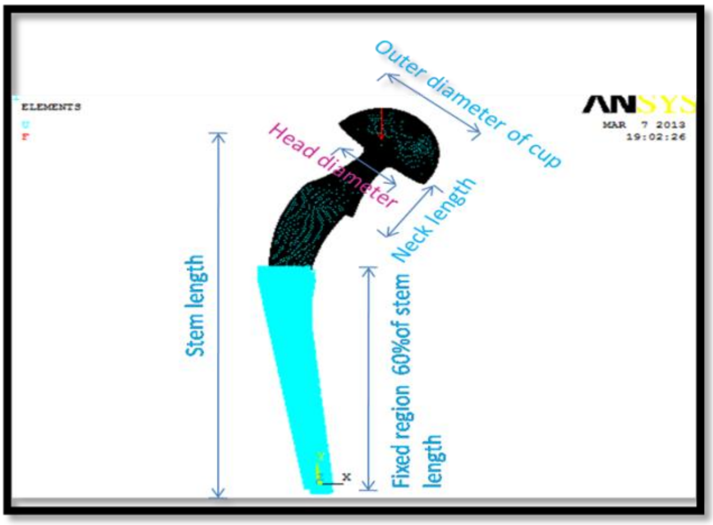

Figure 3. Design parameters and boundary condition, Charnley.

Figure 4. Charmly hip prosthesis, upper view of white acetabulum part (cup), femoral part(stem).

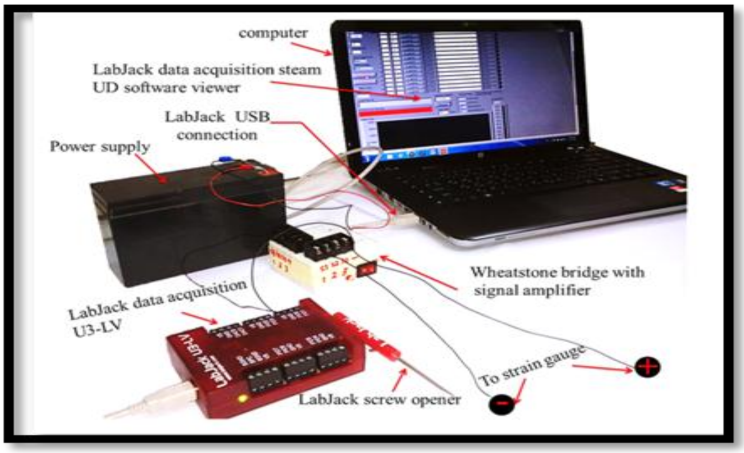

Figure 5. Interface circuit .

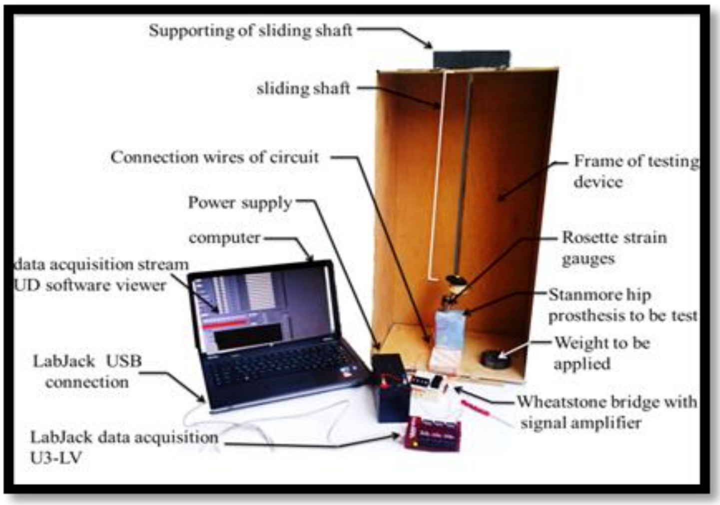

Figure 7. Structure of testing

device.

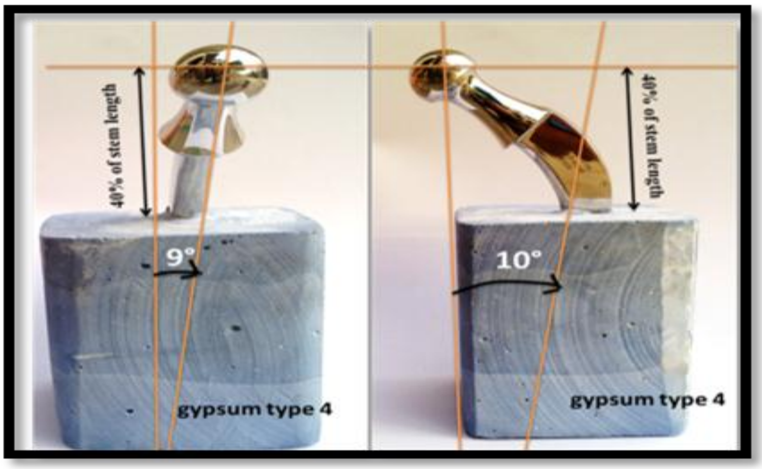

Figure 7. Fixation of hip prosthesis according to ISO-7206 standard where: a- fixation of Charnley hip prosthesis.

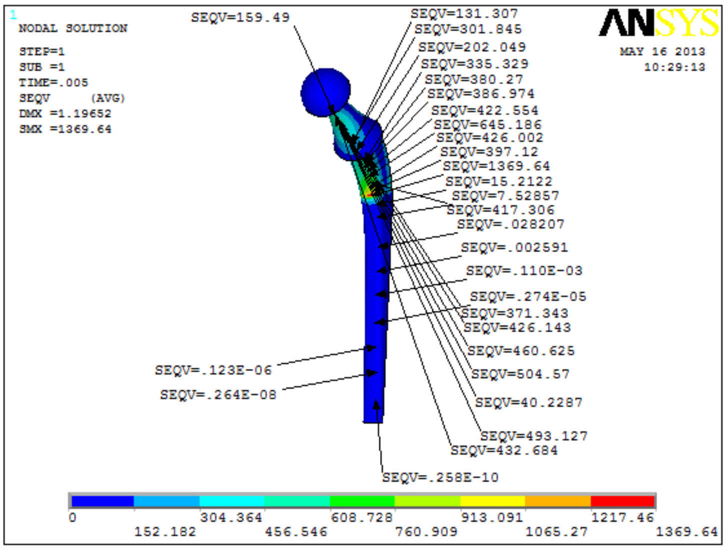

Figure 8. Charnley model effective stress 22mm head diameter.

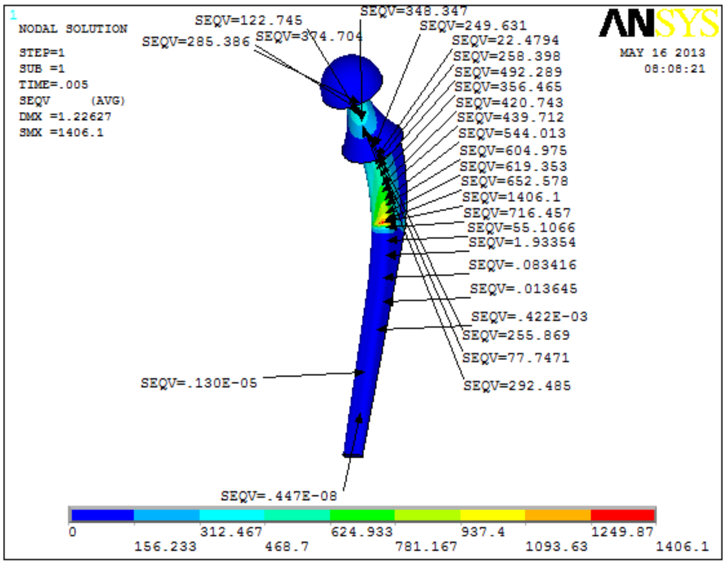

Figure 9. Charnley model effective stress 26mm head diameter.

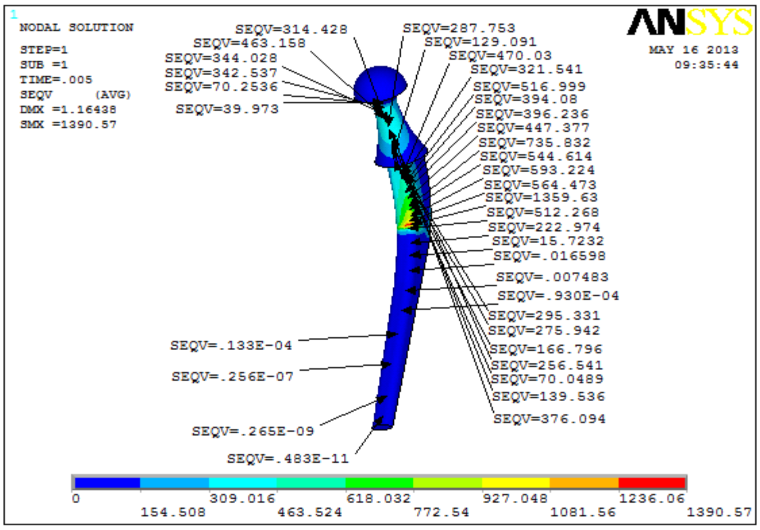

Figure 10. Charnley model effective stress 32 mm neck .lengths.

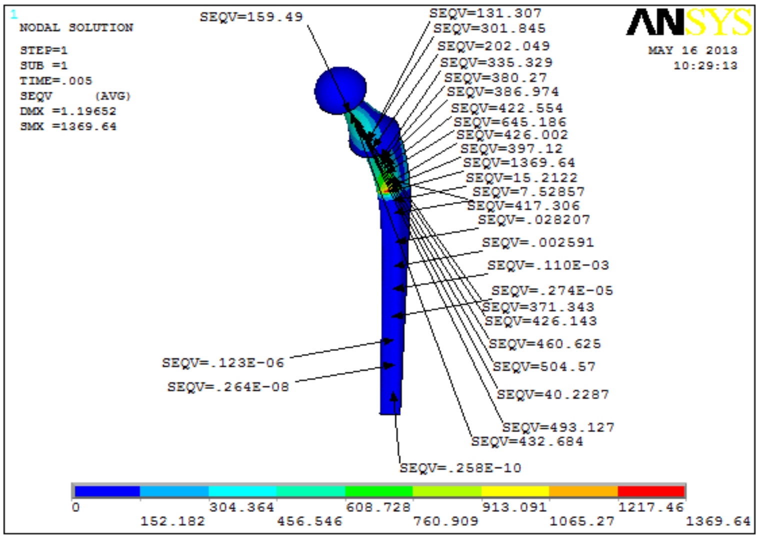

Figure 11. Charnley model effective stress 40 mm neck length.

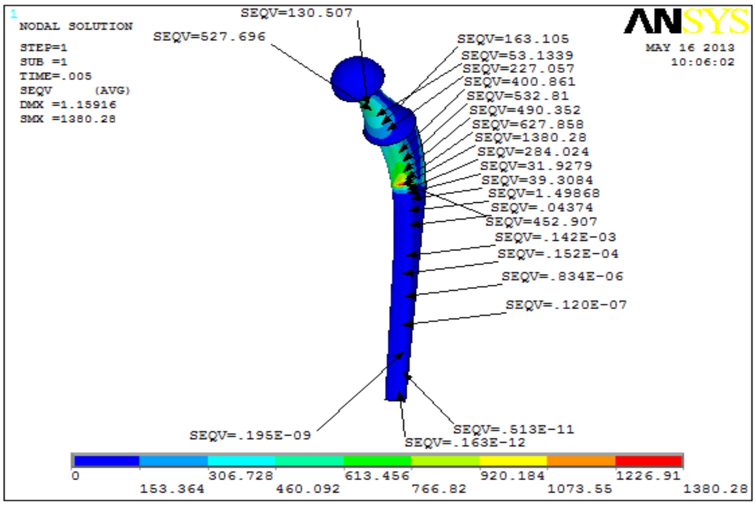

Figure 12. Charnley model effective stress 0.5 neck ratio.

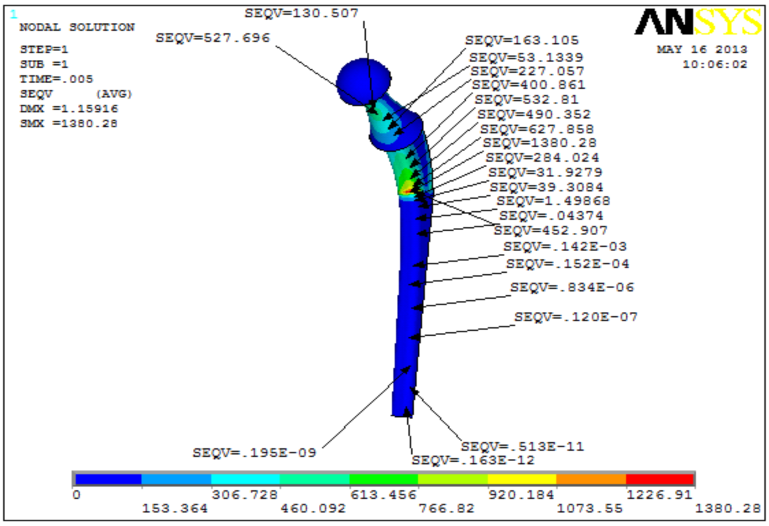

Figure 13. Charnley model effective stress 0.8 neck ratio.

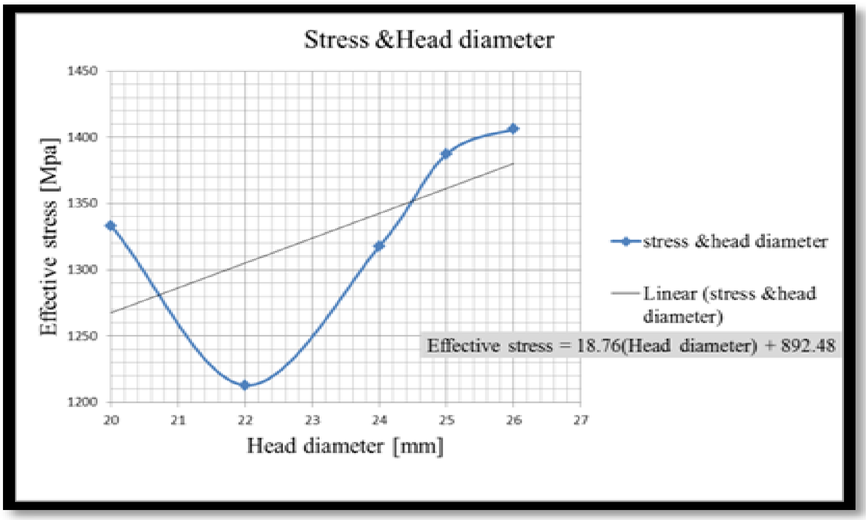

Figure 14. Charnley model effective stress 110 stem length.

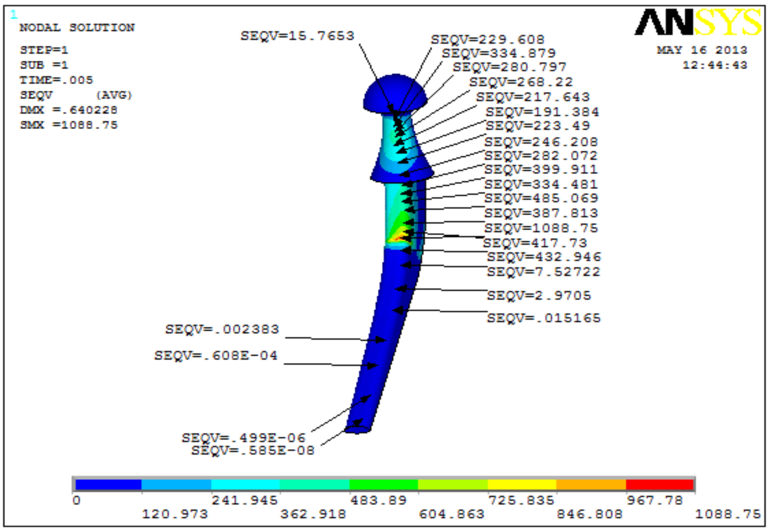

Figure 15. Charnley model effective stress 140 stem length.

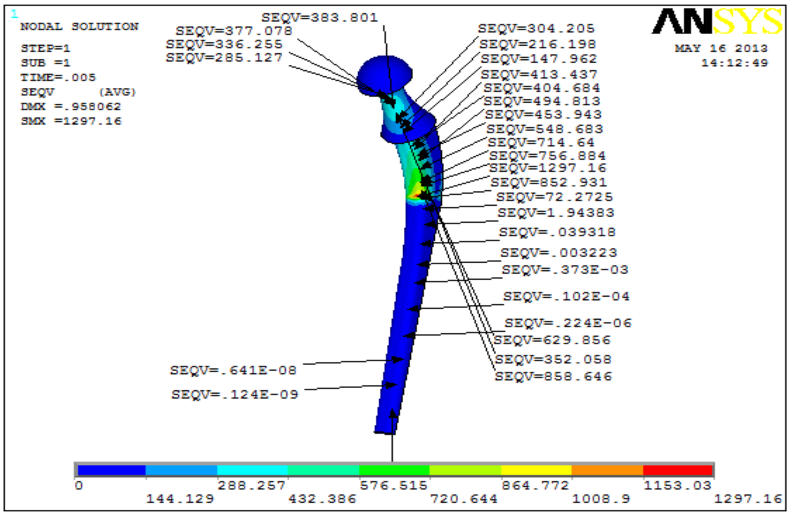

Figure 16. Variation of effective stress of Charnley model with changing head diameter.

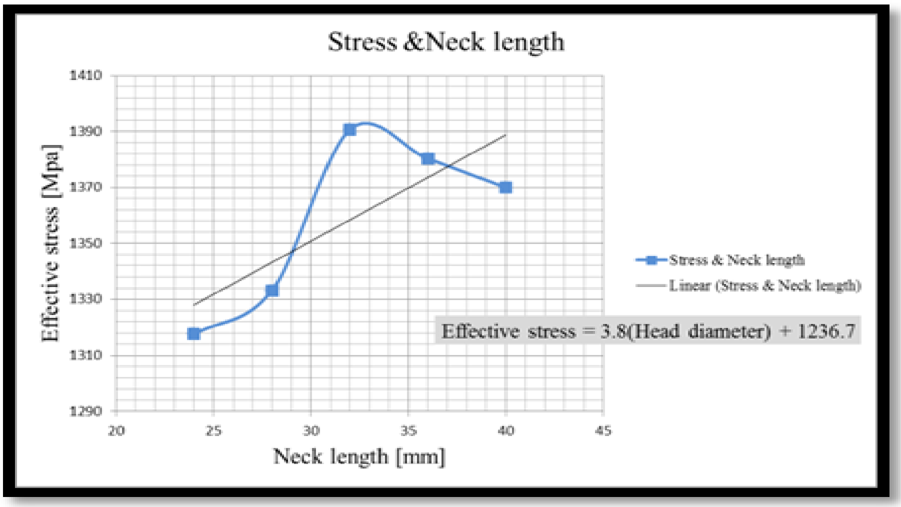

Figure 17. Variation of effective stress of Charnley model with changing neck

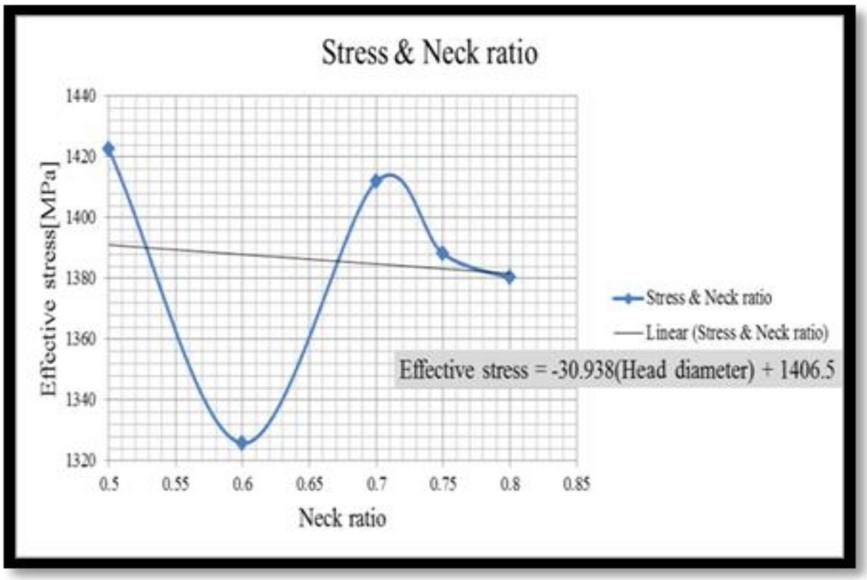

Figure 18. Variation of effective stress of Charnley model with changing stem length.

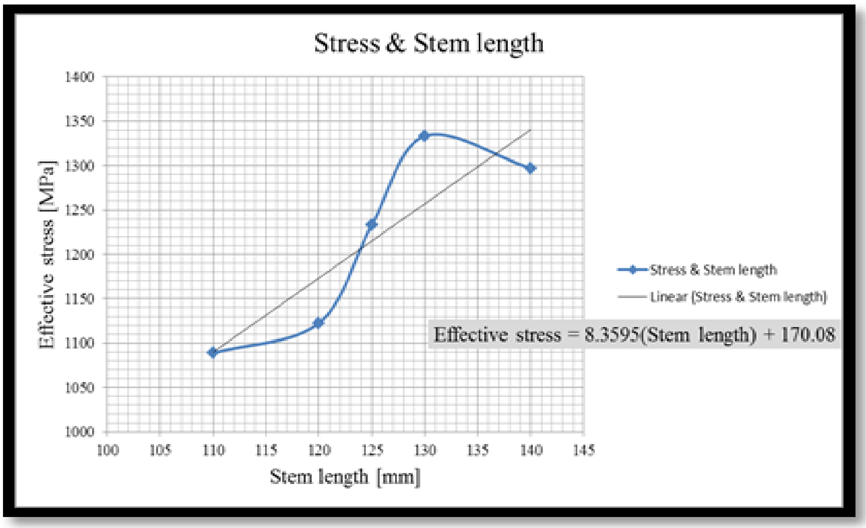

Figure 19. Variation of effective stress of Charnley model with changing neck length.

Table 1. Material properties.

Material	Young's Modulus (GPa)	Poisson's Ratio (v)	Density (g/ cm^3)
Stainless steel	193	0.32	8
UHMWPE	1.2	0.4	0.945

Table 2. Dimensions of Charnley model.

Head Diameter (mm)	Neck Length (mm)	Neck Ratio (mm)	Stem Length (mm)
20	24	0.5	110
22	29	0.6	120
24	32	0.7	125
25	34	0.75	130
26	40	0.8	140

Table 3. Comparison between experimental and numerical results for Charnley design .

Height of Load Dropping (cm)	ANSYS Effective Stress (MPa)	Experimental Effective Stress(MPa)	Error Percent (%)
10	12.15	11.056	9
20	17.183	15.842	7.8
30	21.8131	20.046	8.1