The development of subchondral bone lesions of the medial femoral condyle in horses

A finite element study

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Abstract

Subchondral cystic lesions (SCLs) found on the medial femoral condyle (MFC) are a common problem in horses. However, the mechanism of the growth of SCLs is still debated.

Proposed mechanisms for development of SCLs include osteochondrosis and trauma. Osteochondrosis claimed that the degenerate and necrotic parts of the cartilage led to formation of cartilage flaps and eventually to loss bodies. Small pieces of subchondral bone could be ripped off when a cartilage flap was formed. Trauma claimed that damage to the articular cartilage alone or articular cartilage plus subchondral bone resulted in the formation of subchondral cystic lesions.

In this article, a finite element method was used to evaluate these two proposed mechanism, and try to determine the etiology of SCLs at MFC of horses. A three-dimensional laminated FEA model of MFC joint was built to study the von Mises stress, minimum principal strain, strain energy density in relation to cartilage and cortical bone destructions.

Our study supports that the osteochondrosis mechanism and trauma mechanism both influence the development of SCLs on MFC. The lesions at cartilage are dominated by osteochondrosis; the lesions at cortical bone are dominated by trauma.

Introduction

Cartilage serves as a cushion between the bones of joints, allowing the bones to glide over one another and absorb the shock from physical movements. Subchondral bone is the layer of bone just below the cartilage. Osteoarthritis is caused by the breakdown of cartilage in one or more joints. A subchondral cyst (Figure 1) is a fluid-filled sac that extrudes from the joint, consisting of thickened joint material (mostly hyaluronic acid, a substance found in normal joint fluid that serves to lubricate the joint).

Subchondral cystic lesions found on the medial femoral condyle are a common problem in horses. SCLs are usually located on the weightbearing surface of condyle and are frequently associated with lameness. There is increased blood flow and other changes that develop in the subchondral layer -- subchondral sclerosis (increased bone density), subchondral cyst formation and increased pressure within the bone -- all of which may cause osteoarthritis pain.

The etiology of SCLs is still unclear. In 1940, Freund found evidences that pressure-instrusion of synovial fluid may cause enlargement of cystic lesions. In 1955, Rhaney and Lamb claimed that the “violent impact” between opposing joint surface without cartilage shelter led to bone necrosis. In 1978, Rejno and Stromber claimed that the loss of material in the cartilage was due to the degeneration and necrotic parts of cartilage. In 1996, Baxter suggested that damage to the articular cartilage alone or articular cartilage plus subchondral bone resulted in the formation of subchondral cystic lesions. In this article, a three-demensional laminated finite element model

was used to study the mechanical response of cartilage and subchondral bone under load. The purpose was to evaluate these mechanisms and try to figure out the formation process of SCLs.

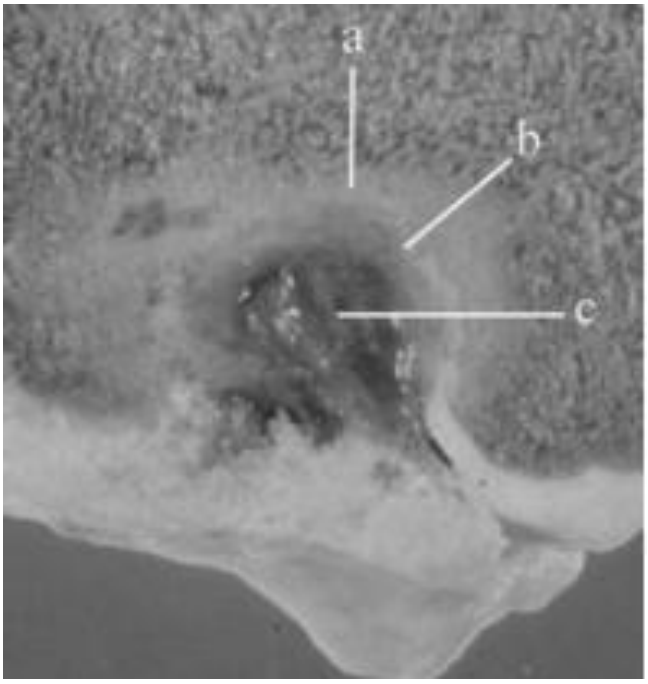


Figure 1 Post mortem sagittal section showing the typical gross appearance of a subchondral cystic lesion. The lesion is surrounded by sclerotic subchondral bone (a). A dense layer of fibrous tissure is found just beneath the bone around the periphery of cyst (b). The centre of cyst is often filled with a gelatinous material (c). (Wallis. T. W 2007)

Materials and methods

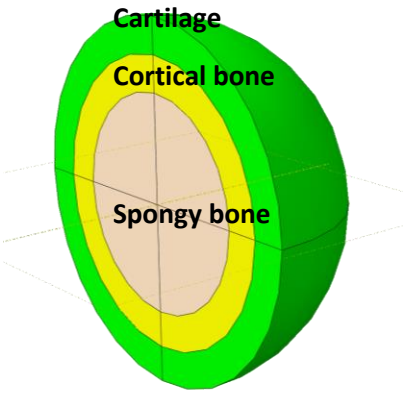
Model description

A three-dimensional laminated finite element model was constructed. The surface of MFC was sphere with radius of 18mm. The surface of foundation was flat plane (Figure 2).The entire height of this model was 9mm. The thickness of cartilage was 2mm, which was constant. Three cartilage/cortical bone thickness ratio were chosen, which were 2:1, 1:1, and 1:2, to implement

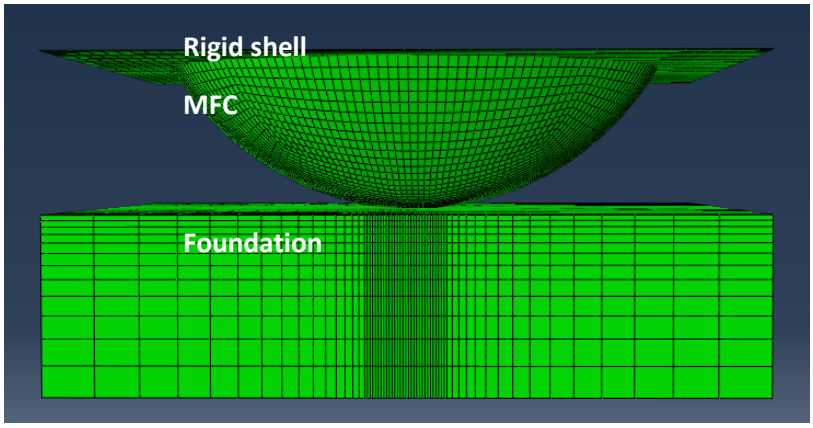
parametrical analysis. Various material properties of foundation were chosen to study how the foundation influenced the mechanical response of bone. The geometry parameter and material properties show below (Table 1). A concentrated force of 1.5kN was implemented perpendicular to the rigid shell. Therefore, the load at MFC was 1.5kN uniform load. All the degrees of freedom were fixed on the bottom of foundation. The rigid shell and MFC could only move along the direction of load.

A CAD software TrueGrid was used to generate this model. TrueGrid is a programming based CAD software. Users could use code to descript the geometry, mesh, point sets, surfaces, material proprieties they need. TrueGrid could read the code and generate the prescribed model (Appendix 1).

After generating the three-dimension model and mesh. An ABAQUS head file (Appendix 2) was needed to define the boundary condition, load, contact, and simulation step.



(a)



(b)

Figure 2. Geometry descriptions. In (a), the green layer is cartilage, the yellow layer is cortical bone, the pink layer is cancellous bone. In (b) the joint includes spherical MFC and flat foundation. The flat plane upon MFC is a rigid shell which is used to generate uniform pressure.

	Cartilage	Cortical bone	Cancellous bone
Thickness (mm)	2	1; 2; 4	6; 5; 3
Young's Modulus (Mpa)	20	20000	1000
Poison's ratio	0.46	0.3	0.3

Table 1 Parameter descriptions.

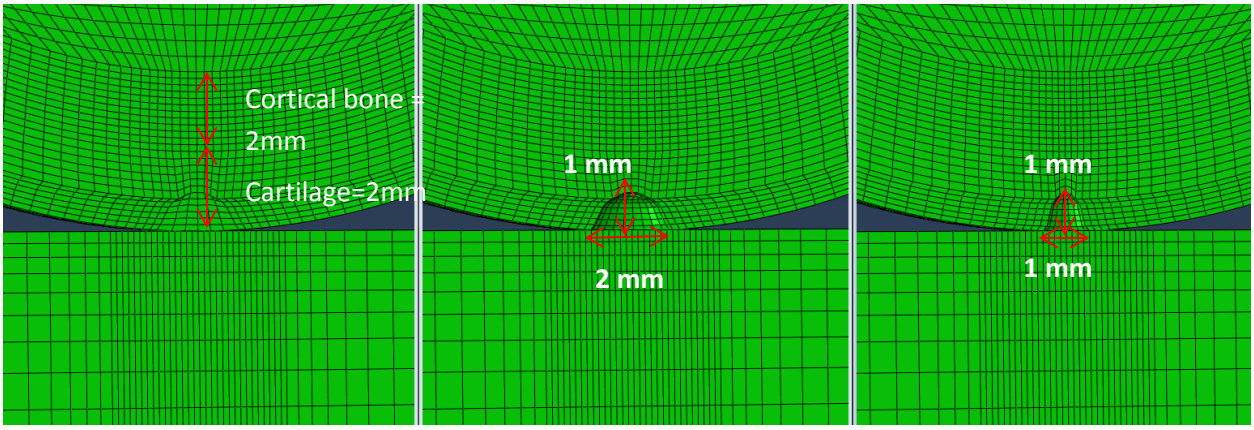
Simulation process

Firstly, parametrical analysis was implemented to figure out a proper Cartilage/Cortical bone thickness ratio and Young's modulus of foundation for further cysts study. Perfect MFC model without cyst was used. Cartilage/Cortical bone thickness ratio were chosen as 1:2, 2:2, and 2:1. Young's modulus of foundation was set as 20Mpa, 200Mpa, 2000Mpa and 20000Mpa. After

determining these two parameters. The proper parameters were implemented into models with various types of cysts to get the van Mises stress distribution, minimum principal strain distribution, strain energy density distribution of the deformed MFC.

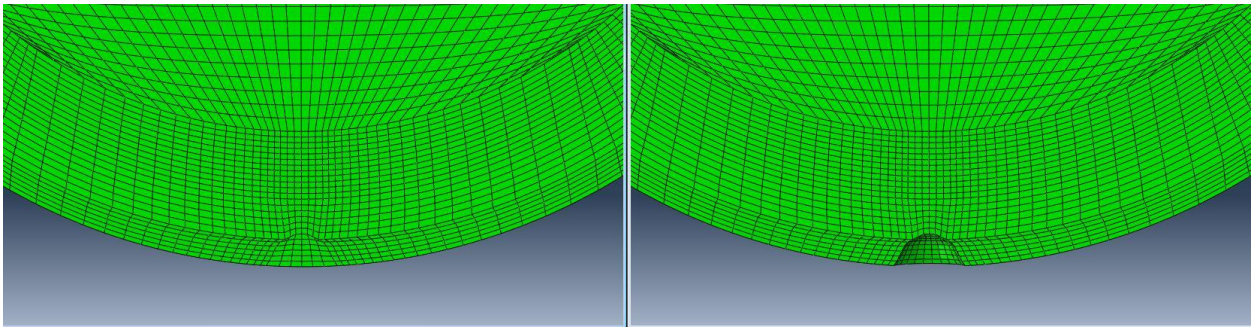
Secondly, Cyst shape analysis was implemented. Various types of SCLs were implemented into the model to study how cyst shape influenced the mechanical resoponse of MFC. Specificly, two models with short and long cysts (Figure 3) were built. The weight/ depth ratio of these two cysts were 2:1 and 1:1 respectively. The von Mises stress distribution, maximum principal strain distrbution, and strain energy density distribution were compared to figure out how different cyst shape influenced the mechanical response of cartilage, cortical bone, and cancellous bone.

Thirdly, cyst transformation analysis was implemented. Models with various geometries (from small cysts to large cysts) and positions (from partial cartilage cyst to entire cartilage cyst, then to cortical bone defect, Figure 4) were made. Again, by comparing the von Mises stress distribution, maximum principal strain distribution, and strain energy density distribution, we would like to study the effect of cyst to the mechanical response of cartilage and cortical bone under load, and how the imperfection at cartilage influences the growth of cyst.

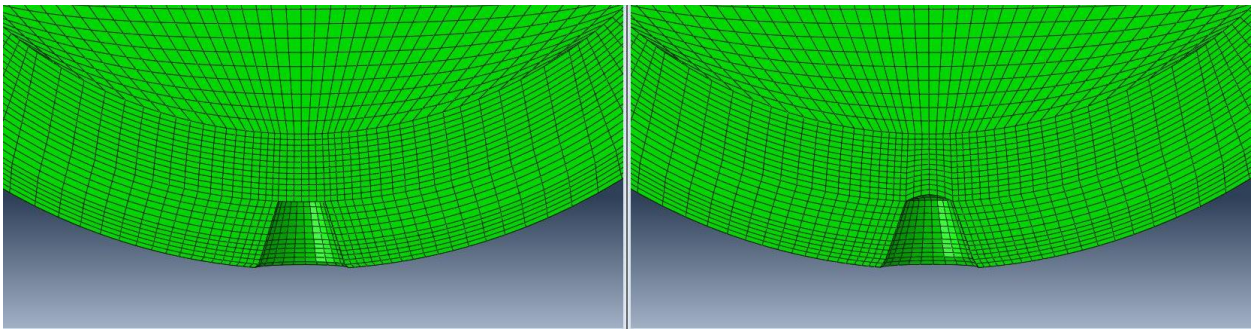


(a) (b) (c)

Figure 3 Cyst shape analysis. (a) Perfect MFC without cyst. (b) Weight/Depth=2/1 cyst. (c)Weight/Depth=1/1 cyst.



(a) (b)



(c) (d)

Figure 4 Four cyst types. (a) Perfect MFC without cyst. (b) Small cyst at cartilage. (c) Entire loss of material at cartilage. (d) Entire loss of material plus a small defect at cortical bone.

Result

Parametrical analysis

The von Mises stress distribution matrix (Figure 5) and maximum von Mises stress table (Table 2) show below. All the maximum von Mises stress appear in the cortical bone. As the Young's modulus of foundation increases, the maximum value of von Mises stress increases. As the

thickness of cortical bone increases, the maximum value of von Mises stress decreases. In the model with the Young's modulus of 2000Mpa and 20000Mpa, after deformation, the maximum values of von Mises stress are similar. 20Mpa is the Young's Modulus of cartilage, which is too soft for the foundation. So, 200Mpa was chosen as the Young's Modulus of foundation, and 1/1 (both are 2mm) was chosen as cartilage/ cortical bone thickness ratio for further research.

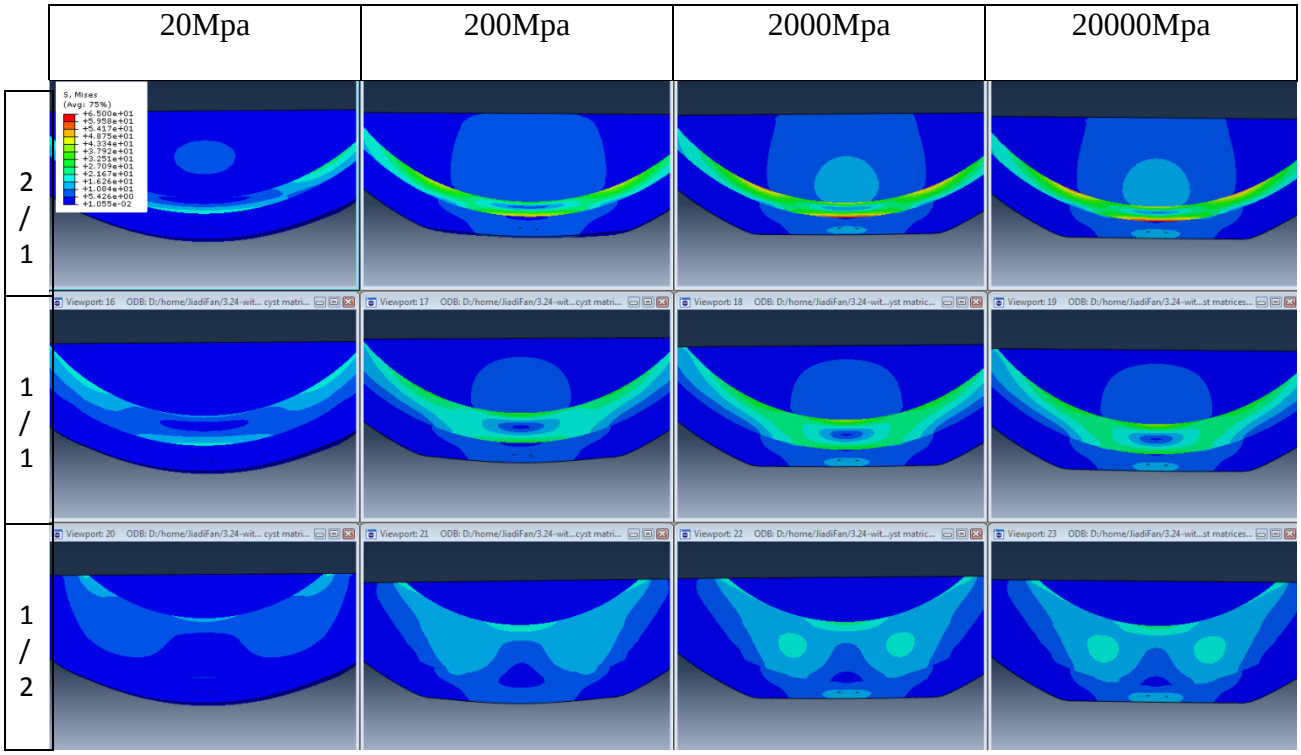


Figure 5 von Mises stress distribution for parametrical analysis

Cartilage/Compact	20Mpa	200Mpa	2000Mpa	20000Mpa
2/1	25.74	53.38	63.64	64.90
1/1	20.81	36.29	43.57	43.57
1/2	20.59	22.90	25.22	25.52

Table 2 Maximum value of von Mises stress

Cyst shape analysis

After parametrical analysis, Young's Modulus of foundation was chosen as 200Mpa, and cartilage /cortical bone thickness ratio was 1/1 and 2/1. Von Mises stress distribution, maximum principal strain distribution, and strain energy density distribution after deformation were studied. (Figure 6, 7, 8 and Table 3 is for cartilage/cortical bone thickness ratio of 1/1; Figure 9, 10, 11 and Table 4 is for cartilage/cortical bone thickness ratio of 2/1)

From Figure 6 and Figure 9, the von Mises stress at cartilage above the cyst was always low for all parameters, and the stress peak was at the edge for all parameters.

From Figure 7 and Figure 10, all the deformation were in the cartilage. However, the cartilage with longer cyst will deform more.

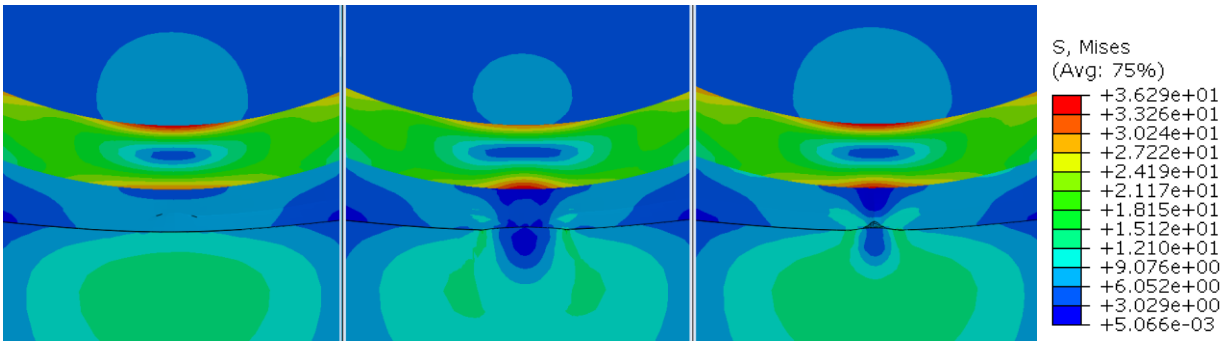
From Figure 8 and Figure 11, the strain energy density above the cyst was also low, and the strain energy density peak was also at the edge for all parameters.

Comparing (a), (b) and (c) in each figure, the cyst generated a low von Mises stress and strain energy density area above the cyst at cartilage. The cyst also generated a von Mises stress and strain energy density peak around the edge of the cyst at cartilage. The "longer" cyst led to a more dramatic change. However, at cortical bone, the cyst made the von Mises stress bone a little more concentrated. From Figure 7-c and Figure 10-c, we noticed that the cyst also generated a low strain area above the cyst, and a strain peak at the edge. However, the change of strain was not obvious in the "short" cyst model (Figure 7-b and Figure 10-b).

Comparing the result of two thickness ratio, the maximum value of von Mises stress (compare Table 3 and Table 4) in a thinner cortical bone model (Cartilage/Cortical bone thickness ratio =

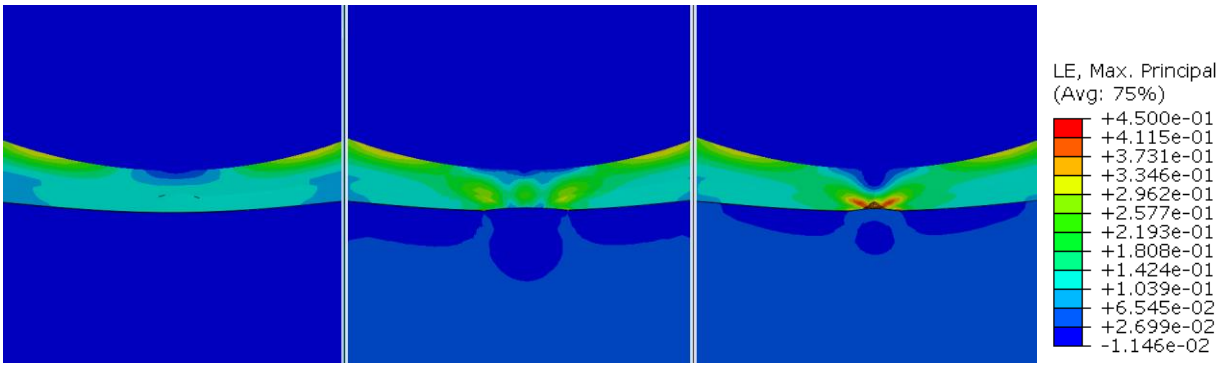
2:1) was increased by about 45% compared with that in a thicker cortical bone model (Cartilage/Cortical bone thickness ratio = 1:1). However, the maximum principal strain and strain energy density didn't change too much.

Cartilage/Cortical bone thickness ratio=1/1 (both are 2mm)



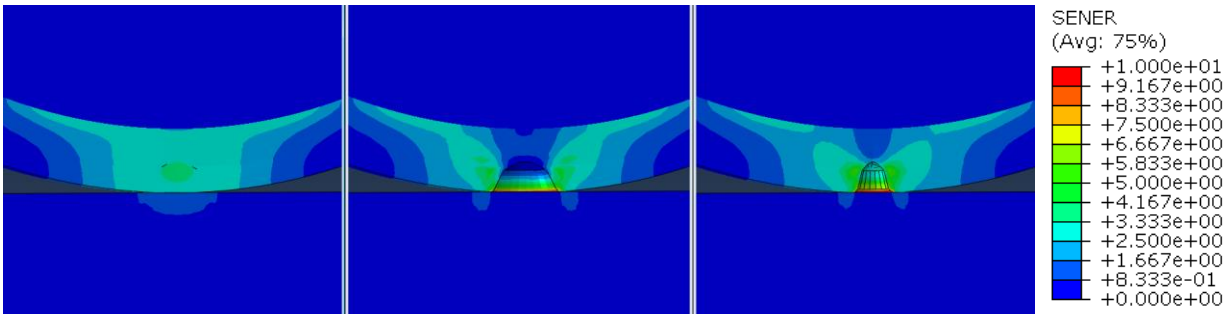
(a) (b) (c)

Figure 6, von Mises stress distribution with cartilage/cortical bone thickness is 1/1. (a)Prefect cartilage without cyst. (b)Weight/Depth of cyst is 2/1. (c) Weight/Depth of cyst is 1/1



(a) (b) (c)

Figure 7, Maximum principal strain distribution with cartilage/cortical bone thickness is 1/1. (a)Prefect cartilage without cyst. (b)Weight/Depth of cyst is 2/1. (c) Weight/Depth of cyst is 1/1



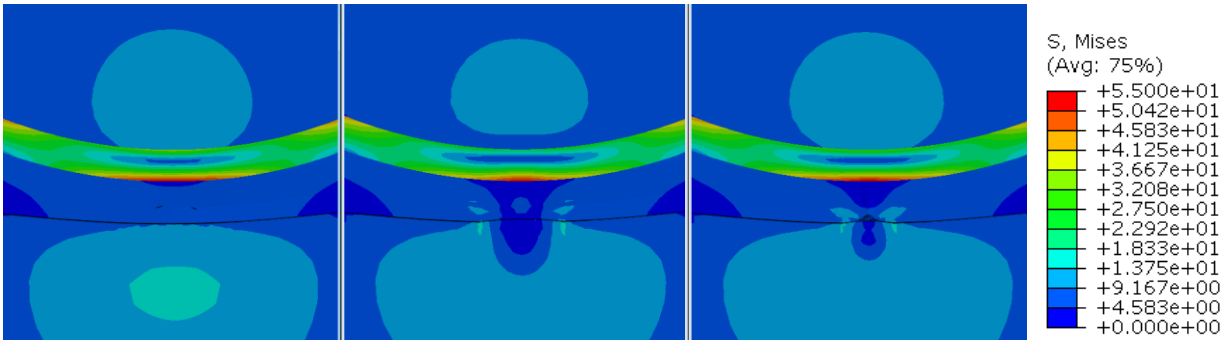
(a) (b) (c)

Figure 8, Strain energy density distribution with cartilage/cortical bone thickness is 1/1. (a) Prefect cartilage without cyst. (b)Weight/Depth of cyst is 2/1. (c) Weight/Depth of cyst is 1/1

Cyst information	Without cyst	W/D=2:1	W/D=1:1
Max value of von Mises stress (Mpa)	37.32	36.29	36.15
Max value of maximum principal strain	0.33672	The max value is 0.4935, but the value in most area is in the range of 0~0.35	The max value is 0.6926, but the value in most area is in the range 0~0.45
Max value of strain energy density	3.42	9.84	13.0

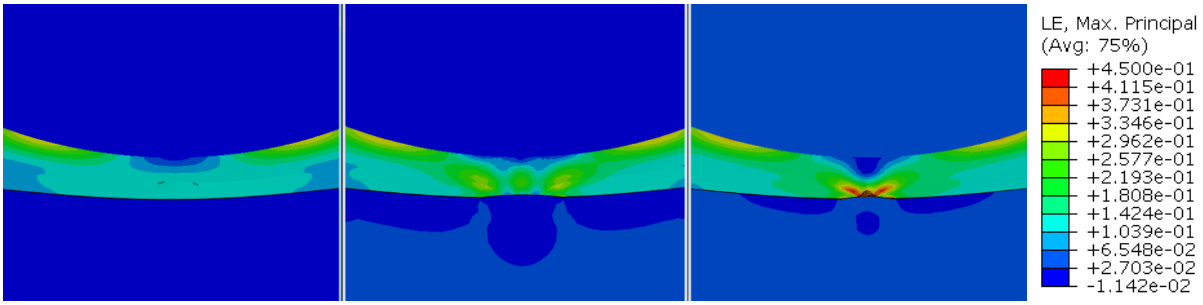
Table 3 Maximum value of three results with cartilage/cortical bone thickness is 1/1.

Cartilage/Cortical bone thickness ratio=2/1 (thickness of cartilage is 2mm)



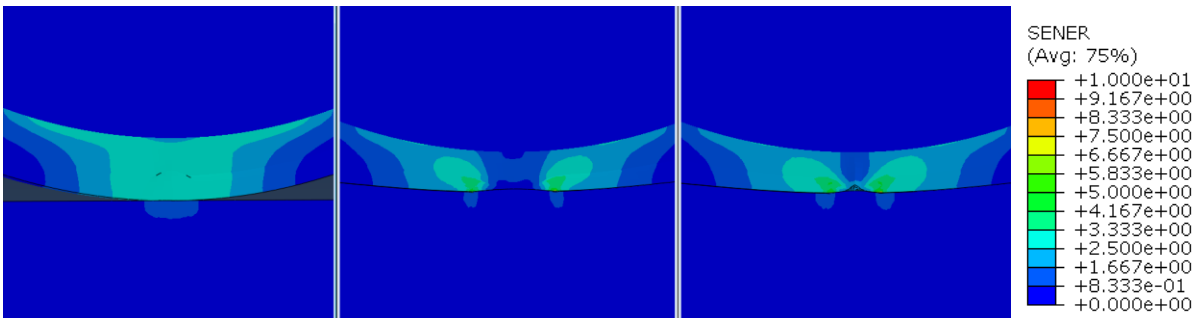
(a) (b) (c)

Figure 9, von Mises stress distribution with cartilage/cortical bone thickness is 2/1. (a) Prefect cartilage without cyst. (b)Weight/Depth of cyst is 2/1. (c) Weight/Depth of cyst is 1/1



(a) (b) (c)

Figure 10, Maximum principal strain distribution with cartilage/cortical bone thickness is 2/1. (a)Prefect cartilage without cyst. (b)Weight/Depth of cyst is 2/1. (c) Weight/Depth of cyst is 1/1



(a) (b) (c)

Figure 11, Strain energy density distribution with cartilage/cortical bone thickness is 2/1. (a) Prefect cartilage without cyst. (b)Weight/Depth of cyst is 2/1. (c) Weight/Depth of cyst is 1/1

Cyst information	Without cyst	W/D=2:1	W/D=1:1
Max Von Mises stress (Mpa)	53.38	52.75	54.32
Max principal strain	0.3346	The max value is 0.4922, but the value in most area is in the range of 0~0.35	The max value is 0.6376, but the value in most area is in the range 0~0.45
Strain energy density	3.325	9.37	11.08

Table 4 Maximum value of three results with cartilage/cortical bone thickness is 2:1.

We would like to focus on the von Mises stress distribution at cartilage. So, a zoom-in contour in the same scale at cartilage (Figure 12, 13) as built. The change of cortical bone thickness didn't influence the von Mises stress distribution at cartilage too much. However, in the thinner cortical bone model, the stress at cancellous bone is larger than that in the thicker one.

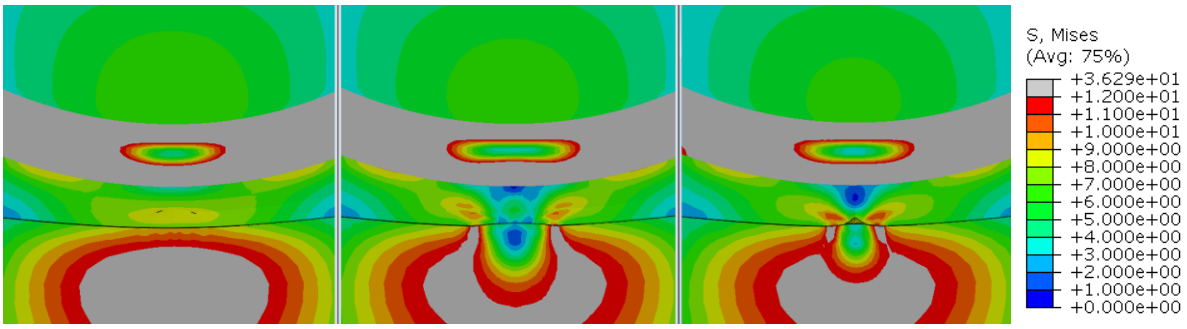


Figure 12 Blow up at cartilage with cartilage/cortical bone thickness is 1:1

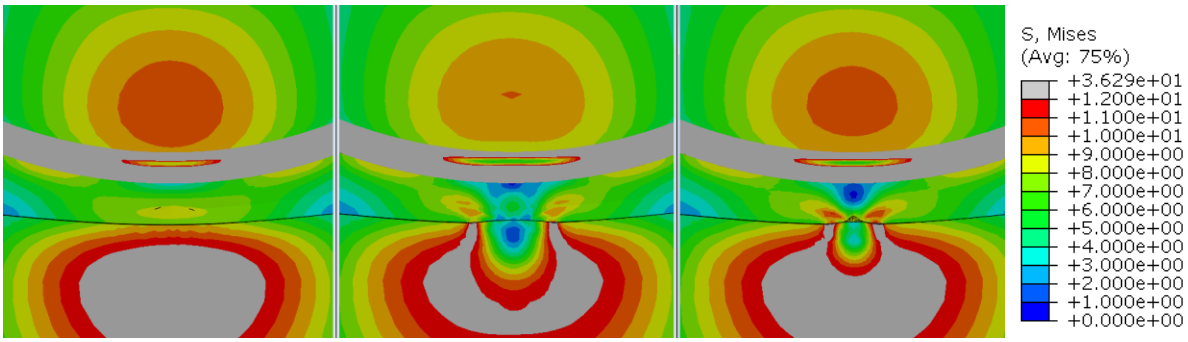


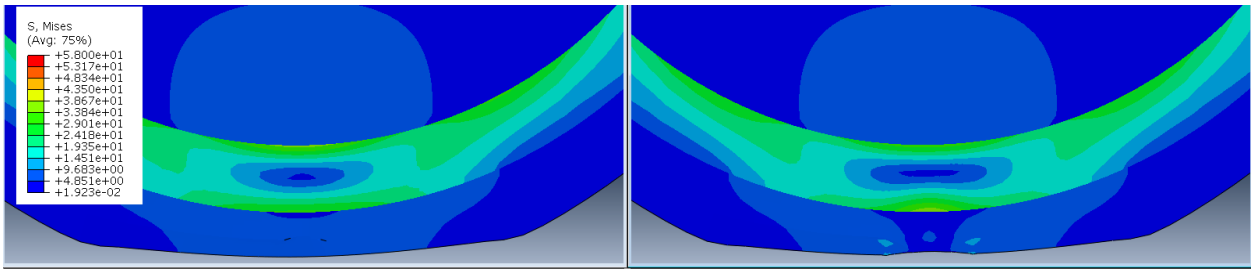
Figure 13 Blow up at cartilage with cartilage/cortical bone thickness is 2:1

Cyst transformation analysis

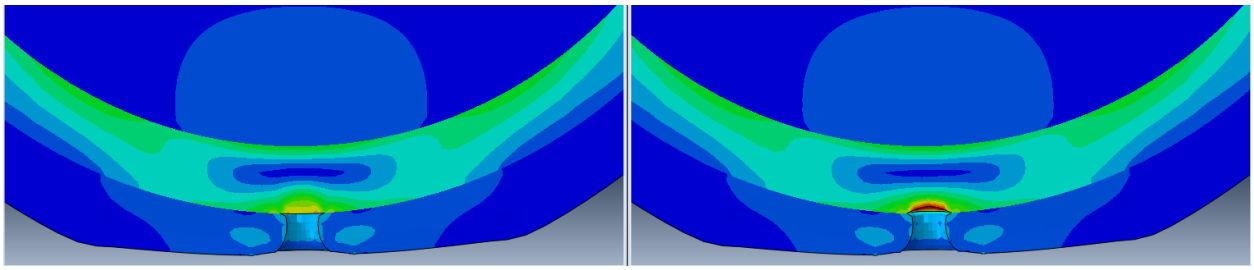
In this part, 200Mpa was used as the Young's Modulus of foundation, and 1/1 as the cartilage/cortical bone thickness ratio. Von Mises stress distribution, maximum principal strain distribution, and strain energy density distributions after deformation were compared. (Figure 14, 15, 16)

In the model with an entire cyst at cartilage, the cyst generated a stress peak at cortical bone (Figure 14-c) and a maximum principal strain peak around the cyst at cartilage (Figure 15-c).

In the model with an entire cyst at cartilage plus a small damage at cortical bone, the cyst also generated a stress peak upon the cyst (Figure 14-d), the area and maximum value were larger than those in model with the entire cyst at cartilage. Similar with (c), the cyst generated a peak of maximum principal strain around the cyst (Figure 15-d). The position and value of strain distribution didn't change too much.

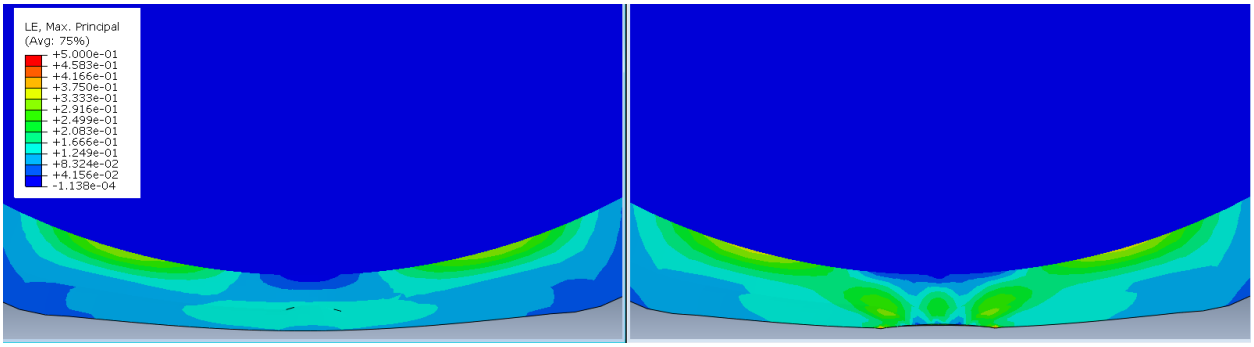


(a) (b)



(c) (d)

Figure 14 von Mises distribution. (a) Perfect cartilage with no cyst. (b) Small cyst at cartilage. (c) Entire loss of material at cartilage. (d) Entire loss of material at cartilage plus a small damage at cortical bone.



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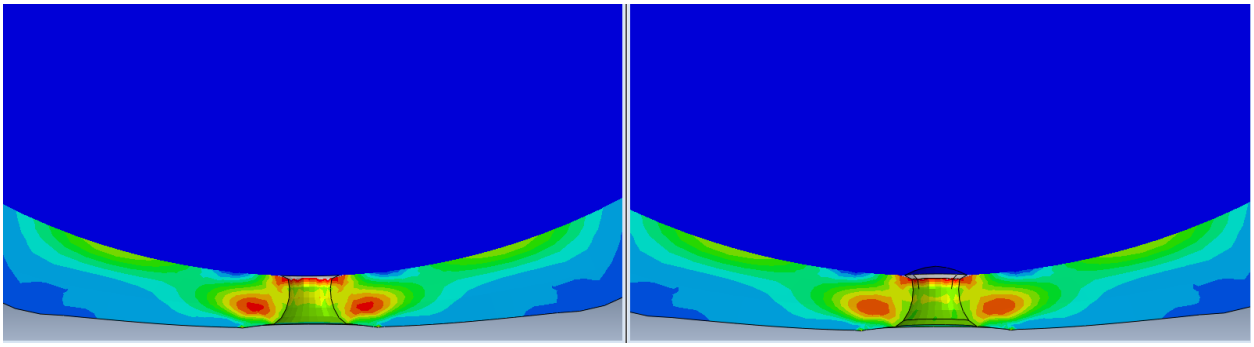
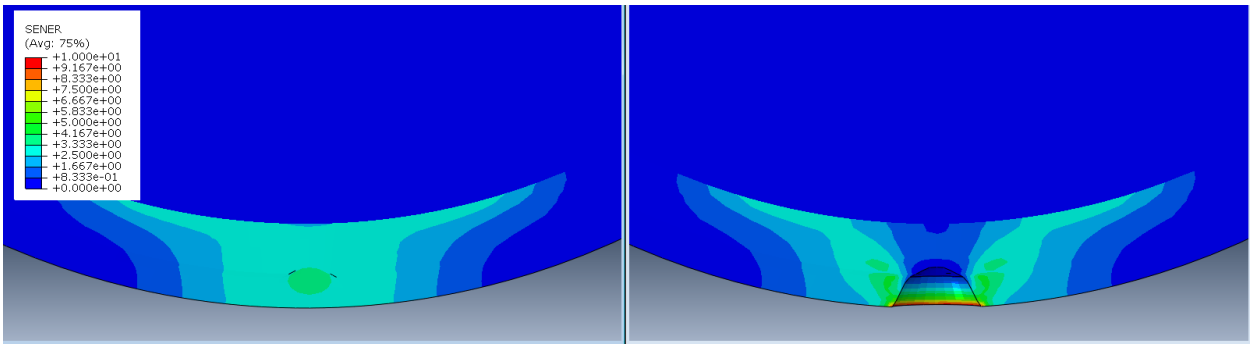
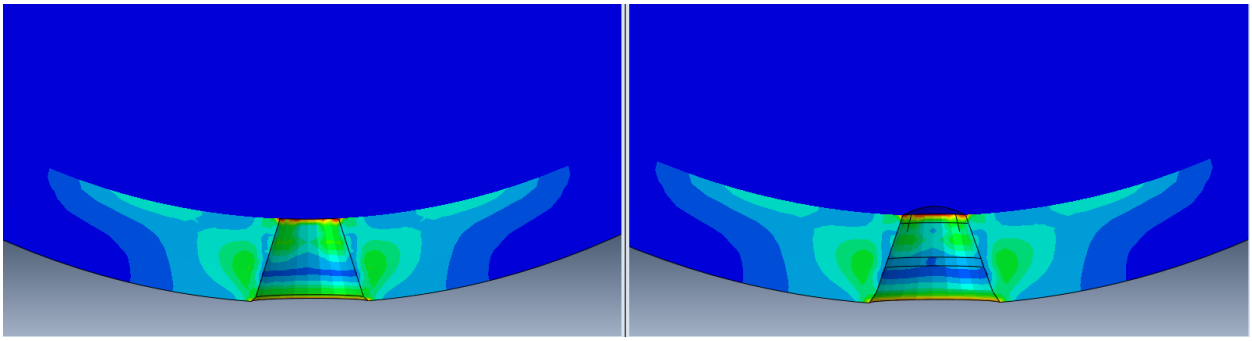


(c) (d)

Figure 15 Maximum principal stain distribution. (a) Perfect cartilage with no cyst. (b) Small cyst at cartilage. (c) Entire loss of material at cartilage. (d) Entire loss of material at cartilage plus a small damage at cortical bone.



(a) (b)



(c) (d)

Figure 16 Strain energy density distribution. (a) Perfect cartilage with no cyst. (b) Small cyst at cartilage. (c) Entire loss of material at cartilage. (d) Entire loss of material at cartilage plus a small damage at cortical bone.

	No cyst (a)	Small cyst at cartilage (b)	Entire loss of material at cartilage (c)	Entire loss of material plus small defect at cortical bone (d)
Max value of von Mises stress (Mpa)	37.32	36.29	50.78	58.60
Max value of Maximum principal strain	0.33672	The max value is 0.4935, but the value in most area is in the range of 0~0.35	The max value is 0.70, but the value in most area is in the range of 0~0.5	The max value is 0.6712, but the value in most area is in the range of 0~0.5

Table 5 Maximum value of von Mises stress and maximum principal strain

Discussion

Parametrical analysis

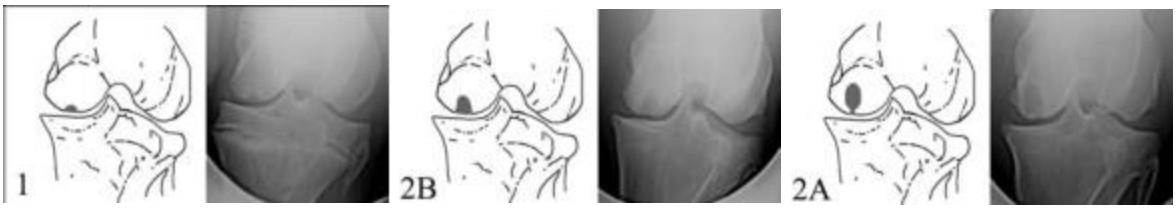
This article focused on the mechanical response at the MFC. As the model was laminated heterogeneous, the thickness of cortical bone influenced the mechanical response at MFC. Actually, the foundation of joint should be a laminated heterogeneous model, as well. However, as foundation was not our interest, it could be defined as a homogenous model with certain

Young's modulus, which should be an average of cartilage (E=20Mpa), cortical bone (E=20000Mpa), and cancellous bone (E=1000Mpa). The purpose of parametrical analysis was to study how Young's modulus of foundation and cartilage/cortical bone thickness ratio influence the stress distribution after deformation, then to determine the proper Young's modulus of foundation and cartilage/cortical bone thickness ratio for further research.

The result from parametrical analysis showed that when the Young's modulus was set as 2000Mpa and 20000Mpa, both the maximum value and the distribution of von Mises stress for three thickness ratio was similar. If the Young's modulus of foundation was higher than 2000Mpa, the change of this parameter will not lead to change, which meant 2000Mpa was too stiff for the foundation. When the Young's modulus of foundation was set as 20Mpa, which was equal to the Young's modulus of cartilage, the von Mises stress was very small. Young's modulus of 20Mpa seemed too soft for the foundation. When the Young's modulus of foundation was set as 200Mpa, the maximum value of van Mises stress was not too big, either too small. So, 200Mpa was the proper Young's modulus for foundation of joint.

Cyst shape analysis

Base on the clinical research, there were various shapes of cysts in the MFC of horse (T.W. Wallis, L.R. Goodrich 2007). Some cysts were shallow (Figure 17-a), some cysts were deep (Figure 17-b), some were small in the surface, but big inside the bone, like a mushroom (Figure 17-c).



(a) (b) (c)

Figure 17 Various types of SCLS

This article focused on the (a) and (b), by implementing the cyst shape analysis to study the effect of cyst shape to the mechanical response of MFC.

From the result of cyst shape analysis, the following conclusions were made: (1) All the low stress and strain energy density areas were above the cyst. (2) All the peak stress and strain energy density areas at cartilage were in the edge of cyst. (3) The change of cortical bone's thickness rarely influenced the mechanical response at cartilage. (4) The cortical bone was like a shell to protect cancellous bone. So, in the bone with a thinner cortical bone, the cancellous bone suffered more von Mises stress.

Cyst transformation analysis

Cyst transformation analysis was the most important session of this article, which could tell us a story about a possible mechanism of how cysts at cartilage grow, and how SCLs was generated. The way that cartilage cells get nutrition is stress. From the result of cyst transformation analysis, the small cartilage defect generated a low stress, low energy, and low strain area above the cyst. Then, the cartilage would have necrosis part because the death of cells. The cyst at cartilage grew because of bone resorbtion, until the entire loss of material at cartilage. This process supported the osteochondrosis theory. After the entire loss of body at cartilage, the subchondral bone lost

the protection of cartilage. This change generated a stress peak at cortical bone, which was 35% higher than that without cyst. This stress peak might generate micro-fracture of cortical bone, and then caused the loss of cortical bone. Under the assumption of this cortical damage, the stress peak in the cortical bone was even 15% higher than the one in the entire cartilage cyst model, which could lead to a further damage at cortical bone. This process supported Rhaney and Lamb's theory and the trauma mechanism.

Strength and limitation

Former research (Durr, Hans, 2004) had used finite element method to study the course and development of subchondral bone cysts. However, their model was two-dimensional axisymmetric model. They did not explain why the cyst at cartilage developed, but only claimed that with the loss of material at cartilage, the development of SCLs was caused by stress-induced micro-fracture. The model in our article was three-dimensional laminated model. We simulated how small cyst at cartilage became large cyst, and then led to the entire loss of material at cartilage. We not only gave hypothesis about how SCLs happened without the shelter of cartilage, but also explained how MFC lost cartilage.

The MFC is highly heterogeneous material. Even though our model was laminated different, but it was homogenous in each lamina. The geometry of our model was prefect sphere. However, the real geometry of MFC should be more complicated. These ideal simplifications would somewhat led to loses of accuracy.

In conclusion, our study claimed that both osteochondrosis theory and trauma theory effected in the formation of subchondral bone. Osteochondrosis mechanism dominated when small cartilage

cyst grew into big cartilage cyst; trauma mechanism dominated after the entire loss of material at cartilage happened, and it was the mechanism that cysts grew at cortical bone.

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Appendix 1: True Grid code

```
abaqus

para mtibia 1 mtit 2 mcart 3 mcort 4 mcanc
5;

abaqmats %mtibia aqelas aqelis  20 0.46;;;

abaqmats %mtit aqelas aqelis 110000 0.3;;;

abaqmats %mcart aqelas aqelis 20 0.46;;;

abaqmats %mcort aqelas aqelis 20000 0.3;;;

abaqmats %mcanc aqelas aqelis 1000 0.3;;;


errmod 2


c parameters

para true 1 false 0;


para r1 18.0 thcart 2 thcort 1 olap 0.000;

para r2 [%r1-%thcart] r3 [%r2-%thcort];

para ellipse 1 facets 2 voidtype %facets;

para cywth 2 cyht 1 cyst %true;



para fullvoid %true;

para cortvoid %false;


if (%fullvoid .eq. %true) then

  para cortvoid %false flat 1 bump 2
cvtype %flat bumpht .20;

endif


para socart 1 socort 2 socanc 3 svoid 4
svoidtop 5 sload 6;

sd %socart sp 0 0 [%r1-%olap] %r1;

sd %socort sp 0 0 %r1 %r2;

sd %socanc sp 0 0 %r1 %r3;

  if (%voidtype .eq. %ellipse) then

    sd %svoid er 0 0 0 0 0 1
[%cywth/2] %cyht;

  else

    para cvoid %nextcrv ct [%cywth/2];

    if (%fullvoid .ne. %true) then

      curd %cvoid lp3 [-%ct-.1] 0 0 [-%ct-.05]
0 [.04*%cyht]

        [-%ct] 0 [.1*%cyht] [-0.7*%ct] 0
[.7*%cyht]

        [-.2*%ct] 0 [.96*%cyht] 0 0
[.97*%cyht];;

    else

      c get the intersection point with the
cortical bone

      para iptoff [%r2*(1-
cos(asin((%cywth/2)/%r2)))];

      if (%cvtype .eq. %flat) then

        c above the intersection point slightly
```

```
      curd %cvoid lp3 [-%ct-.1] 0 0 [-%ct] 0
0.1
       [-%ct] 0 [%thcart+%iptoff] 0 0
[%thcart+%iptoff];;
    else
      curd %cvoid lp3 [-%ct-.1] 0 0 [-%ct] 0
0.1
       [-%ct] 0 [%thcart+%iptoff];;
       arc3 seqnc rt [-%ct] 0
[%thcart+%iptoff]
         rt [-0.5*%ct] 0
[0.707*%bumpht+%thcart+%iptoff]
         rt 0 0 [%bumpht+%thcart+%iptoff];
    endif
  endif
  sd %svoid R3DC 0 0 0 0 0 1 %cvoid 0
365;;
 endif


c factor is to get decent intersection with
cyst opening for ceiling corner
sd %svoidtop sp 0 0 %r1 [%r1-0.8*%cyht]
sd %sload xyplan mz 9;



c Tibia
c went to a center refined region so do it
here.  include viewing, x=0
block 1 2 3 4 5;1 2 3 4;1 2;
    -20 -2.25 0 2.25 20;-20 -2.25 2.25 20;-10
0;
angle 0


para ntibwng 15 ntibcen 30 ntibz 12;
mseq i [%ntibwng-1] [%ntibcen/2-1]
[%ntibcen/2-1] [%ntibwng-1]
mseq j [%ntibwng-1] [%ntibcen-1]
[%ntibwng-1]
mseq k [%ntibz-1]


c make outer els smaller towards center
res 1 1 1 2 4 2 i .85
res 4 1 1 5 4 2 i [1/.85]
res 1 1 1 5 2 2 j .85
res 1 3 1 5 4 2 j [1/.85]


c contact; to avoid equivalencing
c condyle on tibia
sid 1 dummy;
c load on condyle
sid 2 dummy;


sii ;;-2; 1 s
fseti ;;-2; or toptibia


c smaller els at top.  Second one is for block
w/o central refinement
res 1 1 1 5 4 2 k .85
```

```
c res 1 1 1 2 2 2 k .85

c for BCs
nseti ;;-2; or ntop
nseti ;;-1; or nbot

eseti ;;; or etibia
eseti 1 3;;; or emedtibia
eseti 3 5;;; or elattibia

mate %mtibia

endpart

c Bone
block 1 2 3 4;1 2 3 4;1 2;
  -10 -10 10 10;-10 -10 10 10;0 10;

dei 1 2 0 3 4;1 2 0 3 4;;

c now create a central section...
para nwng 12 ncent 36;
para nwng 12 ncent 42;
mseq i [%nwng-1] [%ncent-1] [%nwng-1]
mseq j [%nwng-1] [%ncent-1] [%nwng-1]
mseq k 5

c move wings
mbi -1;-2;;xy -20 -20
mbi -2;-1;;xy -20 -20
mbi -3;-1;;xy  20 -20
mbi -4;-2;;xy  20 -20
mbi -3;-4;;xy  20  20
mbi -4;-3;;xy  20  20
mbi -2;-4;;xy -20  20
mbi -1;-3;;xy -20  20

c create layers for cartilage/cortical
insprt 1 6 1 1
insprt 1 6 2 1

c increase the elements
para nz12 12;
mseq k [%nz12-1] [%nz12-1] 10

c split for cyst
insprt 1 6 1 [%cyht/(%r1-%r2)*%nz12]
c here, "20" is the initial width of the central
portion.  However, use
c 15 to put extra els there and then res to get
smaller near cyst
insprt 1 1 3 [(15-%cywth)/15*%ncent/2]
insprt 1 2 2 [(15-%cywth)/15*%ncent/2]
insprt 1 3 3 [(15-%cywth)/15*%ncent/2]
insprt 1 4 2 [(15-%cywth)/15*%ncent/2]
```

```
c project to the spheres
sfi ;;-1; sd %socart
c don't put top of void on the (layer) sphere
sfi 1 3 0 4 6;; -2;sd %svoidtop
sfi 3 4; 1 3 0 4 6; -2;sd %svoidtop
if (%cortvoid .ne. %true) then
  sfi ;;-3; sd %socort
else
  sfi 1 3 0 4 6;; -3;sd %socort
  sfi 3 4; 1 3 0 4 6; -3;sd %socort
endif
sfi ;;-4; sd %socanc
c outer edges to top plane
for i -1 -4 -1
  sfi -1 0 -6;2 5;%i; sd %sload
  sfi 2 5;-1 0 -6;%i; sd %sload
endfor


c activate this check and one above for
uniform mesh w/ no void
c if (%cyst .eq. %true) then
  c project the surfaces to the cyst
  sfi -3 0 -4;3 4;1 2;sd %svoid
  sfi 3 4;-3 0 -4;1 2;sd %svoid
  sfi 3 4;3 4;-2; sd %svoid
  c bring in center for top of cort. because of
void extra els (=distortion)
  for i 3 4 1
    pb 3 4 %i 3 4 %i xy [0.65*(-%cywth/2)]
[0.65*( %cywth/2)]
    pb 4 4 %i 4 4 %i xy [0.65*( %cywth/2)]
[0.65*( %cywth/2)]
    pb 4 3 %i 4 3 %i xy [0.65*( %cywth/2)]
[0.65*(-%cywth/2)]
    pb 3 3 %i 3 3 %i xy [0.65*(-%cywth/2)]
[0.65*(-%cywth/2)]
  endfor
  c for thick cartilage (th=4), need to bring in
upper center
  if (%thcort .gt. 2.5) then
    mbi -2; 2 5; -4;x 2.5
    mbi -5; 2 5; -4;x -2.5
    mbi 2 5; -2; -4;y 2.5
    mbi 2 5; -5; -4;y -2.5
  endif


  c more elements near the void
  res 2 2 1 3 5 4 i [1/1.1]
  res 4 2 1 5 5 4 i 1.1
  res 2 2 1 5 3 4 j [1/1.1]
  res 2 4 1 5 5 4 j 1.1
  c and make rest more uniform by dist els at
edges of center
  for i 1 4 1
    for j 0 1 1
      res [2-%j] 2 %i [2-%j] 5 %i 2 1
      res [5+%j] 2 %i [5+%j] 5 %i 2 1
```

```
      res 2 [2-%j] %i 5 [2-%j] %i 1 1
      res 2 [5+%j] %i 5 [5+%j] %i 1 1
    endfor
  endfor

  c try to make top elements more square
  relaxi 3 4;3 4;-2;200 .01 1

if (%cyst .eq. %true) then
  if (%fullvoid .ne. %true) then
    c remove the cyst region
    dei 3 4;3 4;1 2;
  else
    c remove all of the cartilage
    dei 3 4;3 4;1 3;
    c project rest of void to the "cyst"
    sfi -3 0 -4;3 4;2 3;sd %svoid
    sfi 3 4;-3 0 -4;2 3;sd %svoid
    relaxi 3 4; 3 4; -3;200 .01 1
    if (%cortvoid .eq. %true) then
      if (%cvtype .eq. %bump) then
        sfi 3 4;3 4;-3; sd %svoid
      endif
    endif
  endif
else
  relaxi 3 4; 3 4; -1;200 .01 1
endif

c contact
sii ;;-1; 1 m
fseti ;;-1; or ball
if (%cyst .eq. %true) then
  sii -3 0 -4;3 4;1 2; 1 m
  sii 3 4;-3 0 -4;1 2; 1 m
  sii 3 4;3 4;-2; 1 m
  fseti -3 0 -4;3 4;1 2; or ball
  fseti 3 4;-3 0 -4;1 2; or ball
  fseti 3 4;3 4;-2; or ball
endif
c since we'll use the cyst geom w/ or w/o the cyst, include the surf
fseti -3 0 -4;3 4;1 2; or cyst
fseti 3 4;-3 0 -4;1 2; or cyst
fseti 3 4;3 4;-2; or cyst

c top, for loading
sii -1 0 -6;; 1 4; 2 s
sii ; -1 0 -6; 1 4; 2 s
fseti -1 0 -6;; 1 4; or bonetop
fseti ; -1 0 -6; 1 4; or bonetop

c will add top by another block for convenience so remove and bb
dei ;;4 5;
```

```
bb 1 2 4 2 5 4 1;
bb 2 5 4 5 6 4 2;
bb 5 2 4 6 5 4 3;
bb 2 1 4 5 2 4 4;
bb 2 2 4 5 5 4 5;

nseti ;;-4; or ndist
nseti -1 0 -4;2 3;; or ndist
nseti 2 3;-1 0 -4;; or ndist

mti ;;1 3; %mcart
mti ;;3 4; %mcort

c make for easy bone BCs and internal viewing
insprt 1 2 3 [%ncent/2-int((15-%cywth)/15*%ncent/2)]
insprt 1 4 3 [%ncent/2-int((15-%cywth)/15*%ncent/2)]
c the bc nodes
nseti -4; -4; -4; or nbonecen
nseti -2; -4; -4; or nboneonx

eseti 1 4;;; or emedball
eseti 4 7;;; or elatball
eseti ;;; or eball
eseti ;;1 3; or ecart
eseti ;;3 4; or ecort

interrupt
endpart

c top part of bone
block 1 2 3;1 2;1 2;
    -10 0 10;-10 10;7 9;

c add elements
mseq i [%ncent/2-1] [%ncent/2-1]
mseq j [%ncent-1]
mseq k [%nwng-1]

bb 1 1 1 1 2 2 1;
bb 1 2 1 3 2 2 2;
bb 3 1 1 3 2 2 3;
bb 1 1 1 3 1 2 4;
bb 1 1 1 3 2 1 5;

c get the top els in slightly
tmei ;; -2;500 .01 1

c contact
sii ;;-2; 2 s
fseti ;;-2; or bonetop

eseti ;;; or eball
eseti ;;; or ecanc
```

eseti 1 2;;; or emedball

eseti 2 3;;; or elatball

mate %mcanc

endpart

c Load plane

block 1 2 3;1 2 3;-1;

-20 0 20;-20 0 20;9;

para nload 50;

mseq i [%nload/2-1] [%nload/2-1]

mseq j [%nload/2-1] [%nload/2-1]

c should be unnecessary but put on same plane since contact there

sfi ;;; sd %sload

c contact

sii ;;; 2 m

fseti ;;; or load

c rigid reference node (why there are 2 regions in i j)

nseti -2;-2;-1; or rignode

eseti ;;; or loadplane

endpart

C put it together

merge

stp .01

Appendix 2: ABAQUS head file

```
**

** These are additional/substitute lines for shell->rigid els

***RIGID BODY, ELSET=erigid, REF NODE=rignode

***ELEMENT, TYPE=R3D4, ELSET=erigid

**

** ----------

*PREPRINT,ECHO=NO,MODEL=YES,CONTACT=YES

** ----------

** in case the opening is large and can't get COPEN values

** add TRACKING THICKNESS=# to SURFACE INTERACTION card

** polished titanium on bone

*SURFACE INTERACTION, NAME=FRIC

*FRICTION

0.41

*SURFACE INTERACTION, NAME=CARTFRIC

*FRICTION

0.01

** ----------

**

**

** Try general contact; could not get orig. contact working 1st step!

*CONTACT

** default to everything (could be longer; whole surf. for CP in viewer)

*CONTACT INCLUSIONS, ALL EXTERIOR

** could specify paris if desired

*CONTACT PROPERTY ASSIGNMENT

,,CARTFRIC

load,bonetop,FRIC

**

** other contactpair options

** ADJUST=0.0, EXTENSIONZONE=0, SMALL SLIDING,

***CONTACTPAIR, INTERACTION=FRIC, TYPE=SURFACETOSURFACE

**topplane, ball

**

***CONTACTPAIR, INTERACTION=BIGFRIC,TIED,ADJUST=0.05,EXTENSIONZONE=0.001

**midashft,midax

****

** ----------

*BOUNDARY, OP=NEW

** bottom of "tibia"

nbot, 1,3,          0.

** symmetry for the bone (no rotation)

nbonecen, 1,2,  0.0
```

nboneonx, 2,, 0.0

** force only Z displacement for loading surface

rignode, 1,2, 0.0

rignode, 4,6, 0.0

**

**

*STEP,AMPLITUDE=RAMP,INC=100,NLGEOM

*STATIC

0.0006,1.0,1.000E-07

**

***BOUNDARY, OP=MOD

**** displacement loading

**rignode, 3,, -1.00

**

*CLOAD, OP=NEW

** distributed load for t20, 1000 total (/7129 nodes)

rignode, 3, -1500

****

*OUTPUT, FIELD, FREQ=99

*NODE OUTPUT

U

*ELEMENT OUTPUT, VARIABLE=preselect

*CONTACT OUTPUT

CSTRESS, CDSTRESS,CDISP,CFORCE

****

**** history outputs, for x-y rpts

**** get output at 4 intervals, FORCED on th

*****OUTPUT, HISTORY, TIME INTERVAL=0.25, TI

**** get them every step because of motion a

*OUTPUT, HISTORY, FREQ=4

***NODE OUTPUT, NSET=rignode

**** might want cf for x-y plots (and moment

**U

***CONTACT OUTPUT

**CSTRESS, CFT, CMT, XT, CAREA

**

*PRINT, FREQ=99, CONTACT=YES

**

** dat output if desired. For this step, ?

**

***NODE PRINT, FREQ=99

**U

***NSET,NSET=cnodes

**1565,1690,1815,5856,5940,6024

***NODE PRINT, NSET=cnodes

**coord

** for t20, get reaction force to make sure =1000

*NODE PRINT, NSET=nbot, FREQ=99

RF

*NODE PRINT, NSET=rignode, FREQ=99

RF

CF

****

**** will generally want all the contact pairs

*CONTACT PRINT, FREQ=2

**CSTRESS

**CDISP

CAREA

**CFT

**CMT

**XT

**

*END STEP

**