



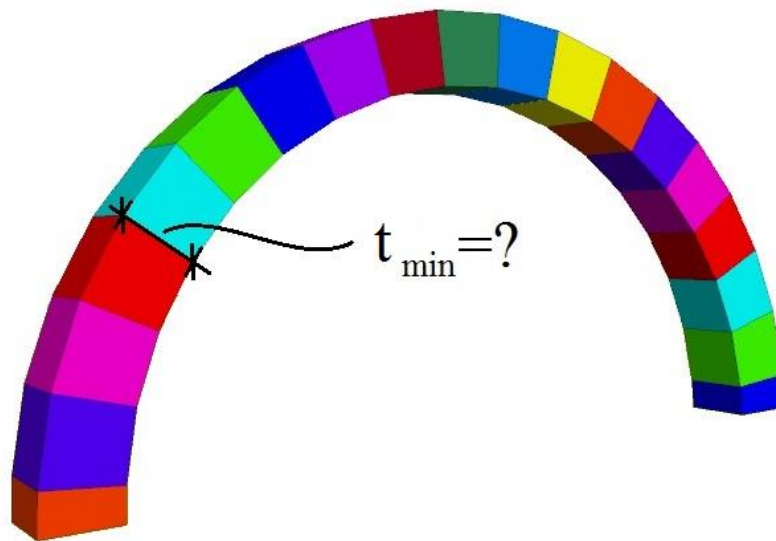
## NUMERICAL MODELS FOR STRUCTURES (BMEEOTMMBO6)

### DEM ANALYSIS OF THE COUPLET-HEYMAN THICKNESS

Homework

*Author:*  
Bence JÁGER

*Supervisors:*  
Dr. Katalin BAGI



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## 1. INTRODUCTION

In the frame of the Numerical Models for Structures course my topic is to analyze the so called Couplet-Heyman thickness of an arch. During the investigation I had used the 3DEC Discrete Element Method software to solve this problem as a 3D problem. Heyman determined the minimum value of the ratio between the thickness of the arch and the radius of the arch related to the gravity line of the arch in 2D.

The conditions which were applied by Heyman are the followings:

He investigated semicircle arches with the variation of the thickness in different radiuses. The thickness of the arches was invariant along the arch. The investigation was done in 2D.

The arch stays on a plane thus the left and the right supports are on the same height. The analyzed structure is made of infinitesimal number of blocks connected to each other with tensionless but with very high frictional contacts. Thus the arch was modeling as an equivalent continuum model in which the blocks were made of rigid material. He analyzed only the stability of the arch under its pure dead load.

Heyman applied the radius of the arch as the distance between the center of the circle and the gravity line of the arch. It can be seen in Figure 1 below:

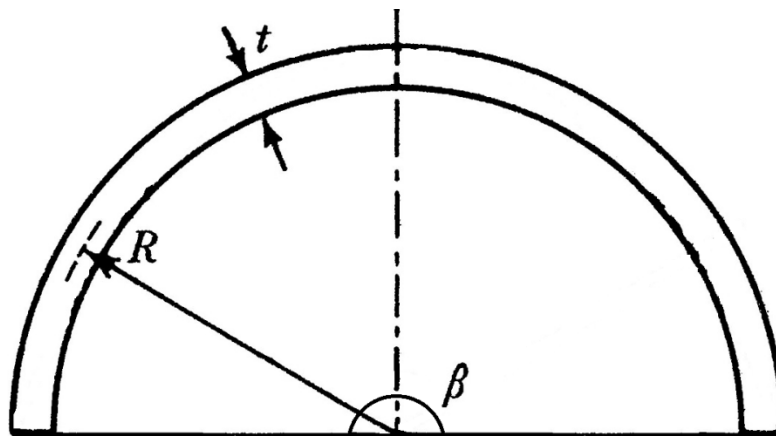


Figure 1: 2D arch applied by Heyman.

Calculation of the Heyman's thickness:  $t_{\min} = 0.105965R$  and  $\beta = 180^\circ$ .

The main goal was to determine the least thickness for a given radius which still provides the stability of the arch but after a bit modification – in the wrong direction – of this value will cause the collapse of the structure under its pure dead load. Heyman gave this thickness value in the proportion of the value of the radius. This suggested proportional band value is 0.105965.

## **2. SOLUTION STRATEGY**

For the purpose of the investigation a discrete element program was applied. This program is the 3DEC. Solving the homework there was no available experimental results to verify the numerical model and its results. During the analysis I had applied some simplifications and differences comparing to the Heyman's conditions (See in Chapter 1) which are demonstrated in the next chapter (See in Chapter 3).

First of all there is a lot of variable which can be analyzed. I had chosen the main parameters which I would like to analyze. These are the thickness and the radius of the arch. The others are also analyzed, but in a lower parameter range. Then I had chosen the geometric parameter range in which the analysis had to be carried out. According to the radius geometric parameter range 9 different cases had to be solved, from 1 meters to 9 meters.

The second step was to build a discrete element model and define the contacts, the dead load and the boundary conditions. The arch is supported vertically by a fixed plane and horizontally along the arch by the length of the stave. For the sake of simplicity in this analysis the radius of the arch is not related to the gravity center of the arch but the half of the thickness of the arch.

The third step was the numerical analysis of the structure in the geometric parameter range. The dead load was taken into the model step by step. Firstly I applied just the 10<sup>th</sup> part of the dead load and then I added once more the 10<sup>th</sup> part of the dead load and so on.

After the examination of each case the minimum thickness can be determined as the proportional value of the radius and it can be compared with the Heyman's thickness.

### 3. DISCRETE ELEMENT MODEL

The models were built in 3DEC. In the followings the numerical models will be presented in sections. Firstly the geometric model will be demonstrated with its simplifications compared with the Heyman's conditions. Then the material model, the contacts, the load and the boundary conditions will be presented in the same way.

#### 3.1. GEOMETRIC MODEL

In the geometric model there are some simplifications about the Heyman's conditions. First of all the numerical model is a 3D model. Furthermore in 3DEC there are just 20 elements are allowed to apply for numerical calculation, which is the limit of the trial version. Thus instead of an equivalent continuum model I had applied 20 elements, one rigid plane at the bottom – as the support – of the arch and 19 rigid elements for creating the arch. Moreover the radius of the arch is related to the distance between the center of the semicircle and the half of the thickness of the arch instead of the Heyman's condition, where the radius is related to the gravity line of the arch. Heyman assumed that the gravity line of the arch is equal to the middle line of the arch due to the infinitesimally small blocks between the contacts. For this reason this last simplification is not a complete simplification – it comes mostly from the limitation of the applied blocks –, because the half line of the thickness of the arch corresponds to the middle line of the arch at the contact points of the numerical model.

During the investigations I had examined two kinds of layouts with using different lengths for the stave. These two values were significantly different. The first was when the stave length was 1 m and in the second case it was 10 m. This investigation was intended to examine the effect of the stave length to the horizontal stability of the arch. In Figure 2 you can see a general layout for each case.

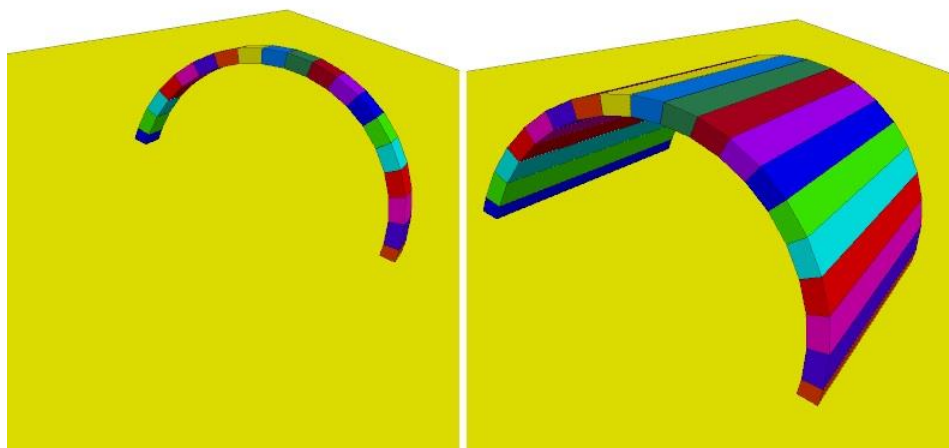


Figure 2: Geometric model with different stave lengths.

### **3.2. MATERIAL MODEL**

In the numerical models rigid elements were applied. After the simplifications of the geometric model, only the rigid elements can satisfy the Heyman's conditions from theoretical and numerical point of view. I had applied sandstone which density is about 2400 kg/m<sup>3</sup>.

### **3.3. CONTACTS**

According to the Heyman's conditions the contacts between the elements have to be rigid, tensionless contacts with high friction. This means that there is no mortar between the blocks. I had examined the rigidity of the contacts from 1 GPa/m to 1000 GPa/m rigidity and the friction of the contacts from 0 to 50 degree. The normal and shear rigidity was equal during the analysis.

### **3.4. LOAD AND BOUNDARY CONDITIONS**

The load is only the pure dead load of the sandstone. The gravity was taken into the numerical model step by step. The numbers of the steps were 10. It was necessary to apply the dead load step by step, because if the dead load is applied in one step it can easily cause the collapse of the structure.

Horizontally, the model was not supported. With the help of different stave length the "support effect" was analyzed which was written in the Chapter 3.1.

Vertically, the model was supported by a rigid block as a plane. This rigid block was fixed in the space.

#### 4. RESULTS

Firstly in Figure 3 below you can see the effect of the two different applied stave lengths. During this investigation the contact normal and shear rigidity was 1 GPa/m and the friction was 50 degree in each cases. The blue line represents the values related to the 1 m and the red one represents the values related to the 10 m stave length. It can be seen that the maximum difference between these diagrams is much less than 1% comparing with the Heyman's suggestion which is negligible. Thus the length of the stave is not important from the analysis of the Heyman's thickness point of view.

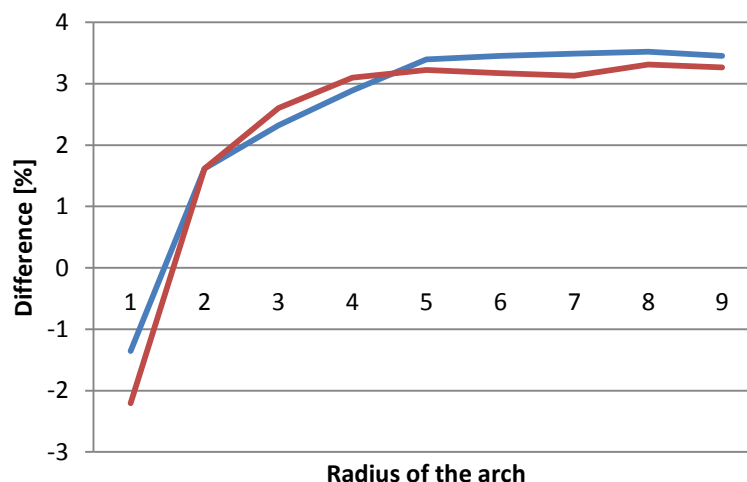


Figure 3: The effect of the two different stave lengths.

Secondly you can see Figure 4 below which shows the numerical results due to different contact rigidities. The blue line demonstrates the multiplication factors for different radiuses related to the contact rigidity 1 GPa/m (red – 10GPa/m, green – 100 GPa/m) and the orange represents the Heyman's suggestion. The multiplication factor gives the ratio between the radius of the arch and the minimum thickness of the arch. I had also analyzed the contact rigidity 1000 GPa/m, but it gave the same results as the green line gives, thus the analysis convergent into the green line.

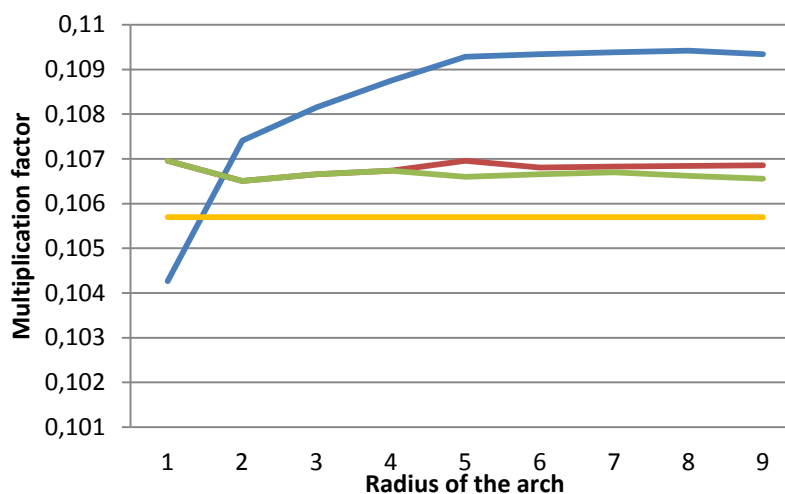


Figure 4: Effect of the different contact rigidity.

The effect of the friction shows a very sharp result. The arch will be stable if the minimum value of the friction is 22 degree. The Figure 5 demonstrates the typical collapse of the structure due to the development of the pure hinge mechanism. This can happen if the friction is more or equal to 22 degree. If not, then the pure hinges can not be developed and the structure will slip out or the combination of this two types of failure can occur. The pure friction collapse can be seen in Figure 6.

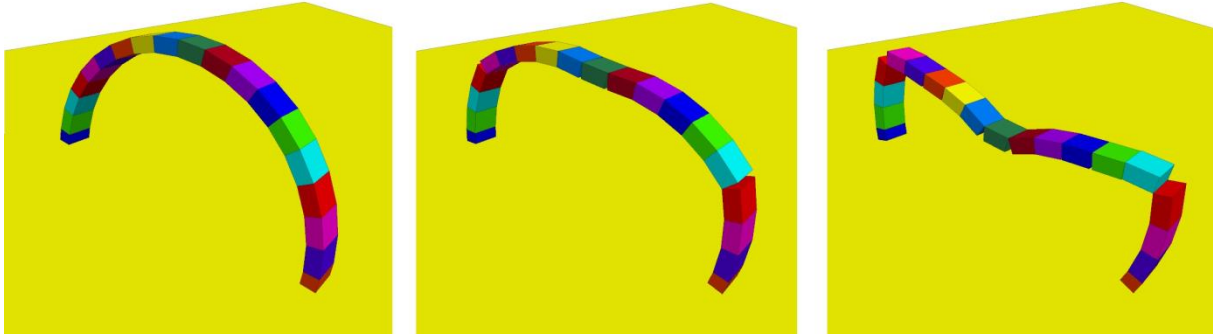


Figure 5: Typical collapse of the structure.

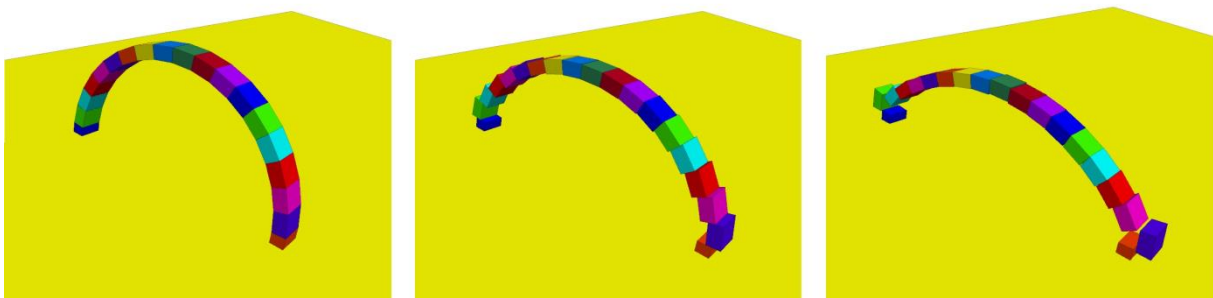


Figure 6: Collapse of the arch due to friction.

Finally the differences from the Heyman's multiplication factor are presented in Figure 7. Each line demonstrates different contact rigidities according to the previous diagram. It can be seen that if we are using contact rigidity value more or equal to 100 GPa/m and friction value more or equal to 22 degree, then the obtained error will not be more than 1% in comparison with the Heyman's suggestion.

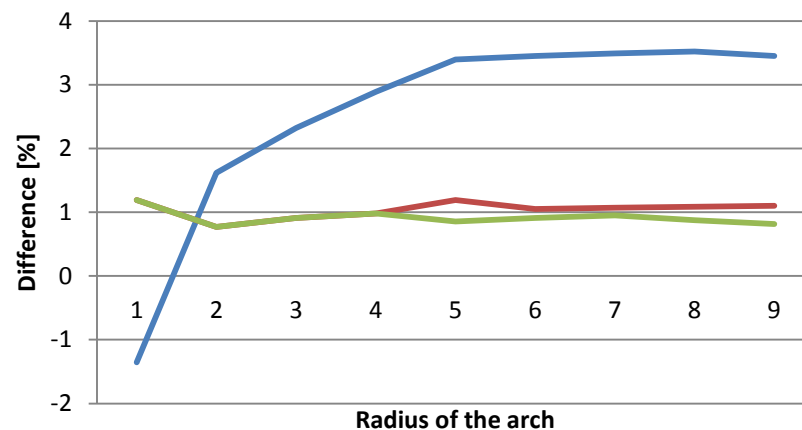


Figure 7: Comparison with the Heyman's suggestion.

The mean value of the received results related to the green line is 0.106666. Compared it with the Heyman's suggestion the accuracy is 0.9187%.

## **5. SUMMARY**

In the frame of the Numerical Models for Structures course my topic was to analyze the so called Couplet-Heyman thickness of an arch. During the investigation I had used the 3DEC Discrete Element Method software to solve this problem as a 3D problem. Heyman determined the minimum value of the ratio between the thickness of the arch and the radius of the arch related to the gravity line of the arch in 2D.

The numerical results show very small differences compared with the Heyman's suggestion. During the analysis it is necessary to apply appropriate contact rigidities. If the contact rigidity is more or equal to 100 GPa/m and friction value is more or equal to 22 degree, then the obtained error will not be more than 1% in comparison with the Heyman's suggestion.

## **6. REFERENCES**

- [1] 3DEC 4.10 Manual
- [2] Turi, N., Bagi, K.: "Boundary conditions in 3DEC", Department of Structural Mechanics, BME, Lecture notes



## 7. INPUT FILE

The geometry of the model was generated with the help of the MATLAB. For sake of simplicity one example is shown below. This example related to a radius and a thickness ( $R_{\text{arch}}=5.2815\text{m}$  and  $t_{\text{min}}=0.563\text{m}$ ).

!Creation of the geometry of the arch with the help of MATLAB

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 pl bl  
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 face 2.351,5.042,-0.700 1.440,5.373,-0.700 1.294,4.830,-0.700 2.113,4.532,-0.700 &  
 face 2.351,5.042,-0.700 2.351,5.042,0.300 1.440,5.373,0.300 1.440,5.373,-0.700 &  
 face 2.351,5.042,-0.700 2.113,4.532,-0.700 2.113,4.532,0.300 2.351,5.042,0.300 &  
 face 1.294,4.830,0.300 1.294,4.830,-0.700 1.440,5.373,-0.700 1.440,5.373,0.300 &  
 face 1.294,4.830,0.300 1.440,5.373,0.300 2.351,5.042,0.300 2.113,4.532,0.300 &  
 face 1.294,4.830,0.300 2.113,4.532,0.300 2.113,4.532,-0.700 1.294,4.830,-0.700  
 pl bl  
 poly &  
 face 1.440,5.373,-0.700 0.485,5.542,-0.700 0.436,4.981,-0.700 1.294,4.830,-0.700 &  
 face 1.440,5.373,-0.700 1.440,5.373,0.300 0.485,5.542,0.300 0.485,5.542,-0.700 &  
 face 1.440,5.373,-0.700 1.294,4.830,-0.700 1.294,4.830,0.300 1.440,5.373,0.300 &  
 face 0.436,4.981,0.300 0.436,4.981,-0.700 0.485,5.542,-0.700 0.485,5.542,0.300 &

```

face 0.436,4.981,0.300 0.485,5.542,0.300 1.440,5.373,0.300 1.294,4.830,0.300 &
face 0.436,4.981,0.300 1.294,4.830,0.300 1.294,4.830,-0.700 0.436,4.981,-0.700
pl bl
poly &
face 0.485,5.542,-0.700 0.000,5.563,-0.700 0.000,5.000,-0.700 0.436,4.981,-0.700 &
face 0.485,5.542,-0.700 0.485,5.542,0.300 0.000,5.563,0.300 0.000,5.563,-0.700 &
face 0.485,5.542,-0.700 0.436,4.981,-0.700 0.436,4.981,0.300 0.485,5.542,0.300 &
face 0.000,5.000,0.300 0.000,5.000,-0.700 0.000,5.563,-0.700 0.000,5.563,0.300 &
face 0.000,5.000,0.300 0.000,5.563,0.300 0.485,5.542,0.300 0.436,4.981,0.300 &
face 0.000,5.000,0.300 0.436,4.981,0.300 0.436,4.981,-0.700 0.000,5.000,-0.700

```

```
!Creation of the support block as a plane
```

```
pl bl
poly brick -0.5,0 -15,15 -35,40
```

```
!Fix the support block
```

```
hide (0,10) (-10,10) (-10,10)
mark region 1
hide region 1
seek
fix region 1
```

```
!Material properties
```

```
prop mat=1 dens=2400
```

```
!Contact properties
```

```
prop jmat=1 kn=1e11 ks=1e11 f=50
```

```
!Definition of the gravity step by step (loading)
```

```
def gra
  grav_lep=10
  gr=0
  loop n(1,grav_lep)
    gr=gr-9.81/grav_lep
    command
      gravity @gr,0,0
      solve rat 1e-5
    end_command
  end_loop
end;
@gra
```