# Design and Finite Element Analysis of H13 Tool Steel Belleville Spring Washer

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**Abstract:** Belleville springs consist of a coned disk, resembling a dinner plate without bottom, which has typical load deflection characteristics. Belleville springs versatility lies in the wide range of spring constants without changing the design. While the applications include disk brakes, clutches, shock-load absorbing bolted assembly, there may be a chance to enhance further applications. The main objective of the project is to design a Belleville spring with the mathematical approach, and modeling them using CatiaV5R20 software. Thereafter, Ansys14.5 software is employed in the static structural analysis of these springs by loading them axially. The safe design is obtained by followed design procedure and also simulation results compared with existing analytical results. With the advent of Belleville Springs, there is a chance to open the door of new spring technologies replacing conventional ones.

**Key words:** Belleville springs, Von-Mises stress, deformation, CatiaV5R20 and Ansys14.5.

## 1. Introduction

Belleville washers were patented in France by Julien F. Belleville of Paris in 1867. Their use throughout the industry is widespread until this day, because they possess certain qualities not obtainable with any other spring washers [1]. Being basically coned disk spring washers, the uses of Belleville washers in packing seals, lathes, and clutches are justified by their ability to maintain a constant force regardless of their dimensional variation caused by wear. Belleville washer's performance is height-sensitive, and with higher cones, there is no increase in spring action, as some may have thought. An increase in height may actually cause an incomplete recovery after deflection, leading to a permanent set of the washer, which may give rise to internal strains, with a subsequent failure of the part [2].

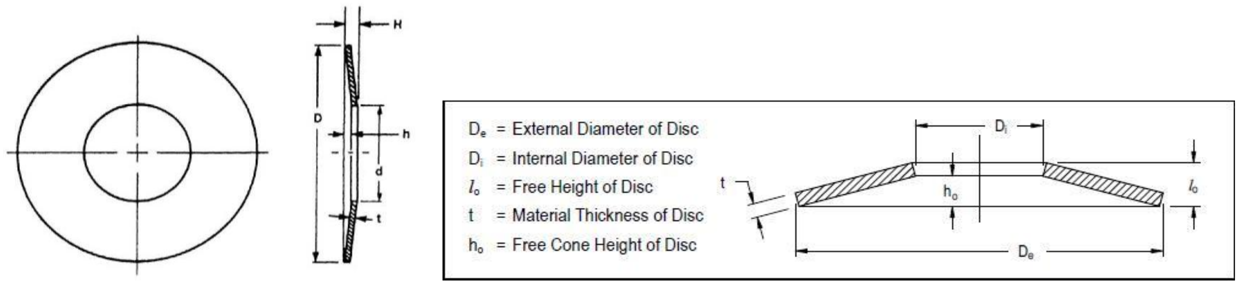


Fig. 1. Belleville Spring Washer Cross Section

A Belleville spring, disc spring, Belleville washer, conical compression washers are all names for the same type of spring. It has a frusto-conical shape which gives the washer a spring characteristic. Belleville washers are typically used as springs, or to apply a pre-load or flexible quality to a bolted joint or bearing. A conical washer can be stacked to create a powerful compression spring. The Belleville washer is often used to support applications that have high loads and insufficient space for a coil spring. Disc springs are conical shaped washers designed to be loaded in the axial direction only [3]. The spring geometry consists of four parameters namely Internal Diameter (d), Outer Diameter (D), Thickness (t), and Height (h) which is shown in Fig. 1.

## 2. Design and Use

Belleville washers are typically used as springs, or to apply a pre-load of flexible quality to a bolted joint or bearing.

Some properties of Belleville washers include: high fatigue life, better use of space, low creep tendency, high load capacity with a small spring deflection and possibility for high hysteresis (damping) by stacking several belleville washers on top of each other in the same direction [2].

They may also be used as locking devices, but only in applications with low dynamic loads, such as down-tube shifters for bicycles. Belleville washers are seen on Formula One cars, as they provide extremely detailed tuning ability. The World War II-vintage GermanJunkers Ju 88 aircraft's single strut, "twisting"-through 90° during retraction/extension main gear made primary use of belleville washers as its main shock absorption mechanism [6]. At least one modern aircraft design, the Cirrus SR2x series, uses a Belleville washer setup to damp out nose gear oscillations (or "shimmy").

Belleville washers have been used as return springs in artillery pieces, one example being the French Canet range of marine/coastal cannon from the late 1800s (75 mm, 120mm, 152 mm).

Another example where they aid locking is a joint that experiences a large amount of thermal expansion and contraction. They will supply the required pre-load, but the bolt may have an additional locking mechanism (like Thread-locking fluid) that would fail without the Belleville.

Belleville washers, when used on the mounting bolts, are also useful as an indicator of swelling or shrinkage of wooden propellers on aircraft (typically experimental aircraft). By torquing their associated bolts to provide a specific gap between sets of washers placed with "high ends" facing each other, a change in relative moisture content in the propeller wood will result in a change of the gaps which is often great enough to be detected visually [6]. As propeller balance depends on the weight of blades being equal, a radical difference in Belleville washer gaps may indicate a difference in moisture content -- and thus weight -- in the adjacent blades.

### 2.1. Stacking

Multiple Belleville washers may be stacked to modify the spring constant or amount of deflection. Stacking in the same direction will add the spring constant in parallel, creating a stiffer joint (with the same deflection) [1]. Stacking in an alternating direction is the same as adding springs in series, resulting in a lower spring constant and greater deflection. Mixing and matching directions allow a specific spring constant and deflection capacity to be designed.

Generally, if **n** washers are stacked in parallel (facing the same direction), the deflection is equal to that of one washer, while the load is **n** times that of one washer. On the other hand, if **n** washers are stacked in series (facing in alternating directions), the deflection is equal to **n** times that of one washer, while the load is equal to that of one washer [8].

### 2.2. Performance Considerations

In a parallel stack, hysteresis (load losses) will occur due to friction between the springs. The hysteresis losses can be advantageous in some systems because of the added damping and dissipation of vibration energy [3]. This loss due to friction can be calculated using hysteresis methods. Ideally, no more than 4 springs should be placed in parallel. If a greater load is required, then factor of safety must be increased in order to compensate for loss of load due to friction. Friction loss is not as much of an issue in series stacks

In a series stack, the deflection is not exactly proportional to the number of springs. This is because of a bottoming out effect when the springs are compressed to flat. The contact surface area increases once the spring is deflected beyond 95%. This decreases the moment arm and the spring will offer a greater spring resistance. Hysteresis can be used to calculate predicted deflections in a series stack [6]. The number of springs used in a series stack is not as much of an issue as in parallel stacks.

Belleville washers are useful for adjustments because different thicknesses can be swapped in and out and they can be configured to achieve essentially infinite tunability of spring rate while only filling up a small part of the technician's tool box [4]. They are ideal in situations where a heavy spring force is required with minimal free length and compression before reaching solid height. The downside, though, is weight, and they are severely travel limited compared to a conventional coil spring when free length is not an issue.

A wave washer also acts as a spring, but wave washers of comparable size do not produce as much force as Belleville washers, nor can they be stacked in series.

## 2.3. Disc Springs

A disc spring (sometimes called a "Belleville washer" after the inventor) consists primarily of a convex disc supported at the outer periphery by one force and an opposing force on the center of the disc [3]. Disc springs are used singly, or in stacks, to achieve a desired load and travel. The advantage of a disc spring is that it generates high force in a very short spring length and with minimal movement when compressed. All Century Spring disc springs are subject to exacting manufacturing and quality control standards [2]. All discs are preset so that they will not significantly relax under load over time. Century Spring also offers pre-stressed disc springs specifically sized for use with bolts.

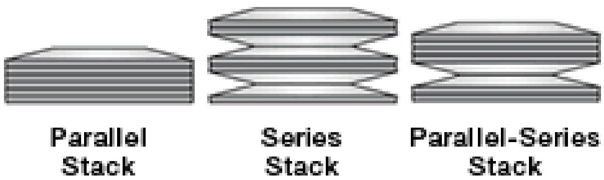


Fig. 2. Arrangement of Belleville Springs

All Spring Belleville Washers are manufactured in 300 Series Stainless Steel, which offers good corrosion resistance for most applications. Additionally, Spring Belleville Washers are passivated to remove contaminants and further improve resistance to corrosion. When your compression spring application requires a high load in a small space, Lee Spring's Belleville Washers can be the solution [6]. Their conical configuration enables them to support high loads with relatively small deflections and solid heights compared to helical springs. Belleville Washer are often used to solve vibration, thermal expansion, relaxation and bolt creep problems. Spring Belleville Washers are manufactured from 300 Series Stainless Steel. This alloy offers good corrosion resistance for most applications [8]. Additionally, Spring Washers are passivated in accordance with specification ASTM A967 (supercedes QQ-P-35) to remove contaminants and further improve resistance to corrosion. 300 Series Stainless Steel is slightly magnetic and is recommended for any applications where the temperature is below 500° F (260° C). Additional load flexibility can be achieved by stacking Belleville Washers in various configurations. Belleville Washers can be used in four different ways:

- Single: One washer
- Parallel: All washers stacked the same way
- Series: All washers stacked opposite each other
- Series-Parallel: A combination of the two

## 3. Designing of Belleville Spring Washer

The design of Belleville spring requires iteration. Trail values of $R_0$ and h/t ratio must be chosen. It is possible to estimate thickness required to obtain a particular force at the flat position from [2]

$$t = \frac{1}{10}\sqrt[4]{\frac{F_{flat} \times D_0^2}{132.4 \times h/t}}$$

Generally we choose h/t ratio 1.414 for approximate constant value, centered around flat position [2]. h/t=1.414

Nominal force applied on spring = 45 N
Percentage deviation of force from 100% = ±5%
The spring must fit in 31.75 mm diameter hole
The material chosen is H-13 hot working tool steel
We may even choose austenitic stainless steel or hardened high carbon steel as materials based up on requirements.

Table 1. Properties of H-13 hot working Tool Steel

| Properties | Values |
|---|---|
| Young's modulus-E | 210 GPa |
| Density | 7861 Kg/m$^3$ |
| Thermal conductivity-k | 29w/mk |
| Poisson ratio-µ | 0.273 |
| Tensile strength-yield | 1000-1450 MPa |

Assuming Rd=diameter ratio=2 (for max energy storage)
Let $D_0$=30.5 mm leaving clearance.
h/t ratio=1.414 constant spring force required.
Force variation ±5%
Thereby deflection is in range of 65%-135%.

$$t = \frac{1}{10}\sqrt[4]{\frac{F_{flat} \times D_0^2}{132.4 \times h/t}} = \frac{1}{10}\sqrt[4]{\frac{45 \times 30.5^2}{132.4 \times 1.414}}$$

t =0.386mm

h/t=1.414; h=0.386  1.414=0.545mm

$y_{min}$=0.65h=0.354mm

$y_{max}$=1.35h=0.735mm

$$K_1 = \frac{6}{\pi \ln R_d}\left[\frac{R_d - 1}{R_d}\right] = \frac{6}{\pi \ln 2}\left[\frac{2-1}{2}\right] = 0.689$$

$$K_2 = \frac{6}{\pi \ln R_d}\left[\frac{R_d - 1}{\ln R_d} - 1\right] = \frac{6}{\pi \ln 2}\left[\frac{2-1}{\ln 2} - 1\right] = 1.22$$

$$K_3 = \frac{6}{\pi \ln R_d}\left[\frac{R_d - 1}{\ln R_d}\right] = \frac{6}{\pi \ln 2}\left[\frac{2-1}{\ln 2}\right] = 0.689$$

Compressive stress $\sigma_c = -\frac{4Ey}{K_1 \times D_0^2\left(1-\vartheta^2\right)}\left[K_2\left(h-\frac{y}{2}\right)+K_3 t\right]$

$$\sigma_c = -\frac{4\times 210\times 10^3 \times 0.735}{0.689\times 30.5^2\left(1-0.3^2\right)}\left[1.22\left(0.545-\frac{0.735}{2}\right)+1.378(0.386)\right]$$

$$\sigma_c = -792.27 MPa < \sigma_y$$

Inner tensile stress $\sigma_{ti} = -\frac{4Ey}{K_1 \times D_0^2\left(1-\vartheta^2\right)}\left[-K_2\left(h-\frac{y}{2}\right)+K_3 t\right]$

$$\sigma_{ti} = -\frac{4\times 210\times 10^3 \times 0.735}{0.689\times 30.5^2\left(1-0.3^2\right)}\left[-1.22\left(0.545-\frac{0.735}{2}\right)+1.378(0.386)\right]$$

$$\sigma_{ti} = 333.8 MPa < \sigma_y$$

Outer tensile stress $\sigma_{to} = -\frac{4Ey}{K_1 \times D_0^2\left(1-\vartheta^2\right)}\left[K_4\left(h-\frac{y}{2}\right)+K_5 t\right]$

$$\sigma_{to} = -\frac{4\times 210\times 10^3 \times 0.735}{0.689\times 30.5^2\left(1-0.3^2\right)}\left[1.15\left(0.545-\frac{0.735}{2}\right)+1(0.386)\right]$$

$$\sigma_{to} = 618 MPa < \sigma_y$$

$$R_d = D_0/D_i$$

$$2 = 30.5/D_i$$

$$D_i = 15.25\text{mm}$$

**Spring Dimensions:** Thickness of the spring, **t =0.386 mm,** Free cone height, **h=0.545 mm,** Outer diameter of the spring **$D_0$ = 30.5mm,** Inner diameter of the spring **$D_i$ = 15.25mm**

## 4. Modeling of Belleville Spring Washer Using CatiaV5R20

The Belleville Washer may be generated using shaft tool. The half sketch is drawn and then the entire washer is generated. This task illustrates how to create a shaft that is a revolved feature. You need an open or closed profile, and an axis about which the feature will revolve. Note that you can use wireframe geometry as your profile and axes. Select the open profile. Click the Shaft icon. The Shaft Definition dialog box is displayed. The application displays the name of the selected sketch in the Selection field from the Profile frame. For the purposes of our scenario, the profile and the axis belong to the same sketch. Consequently, you do not have to select the axis. You can create shafts from sketches including several closed profiles. These profiles must not intersect and they must be on the same side of the axis. If needed, you can change the sketch by clicking the field and by selecting another sketch in the geometry or in the specification tree.

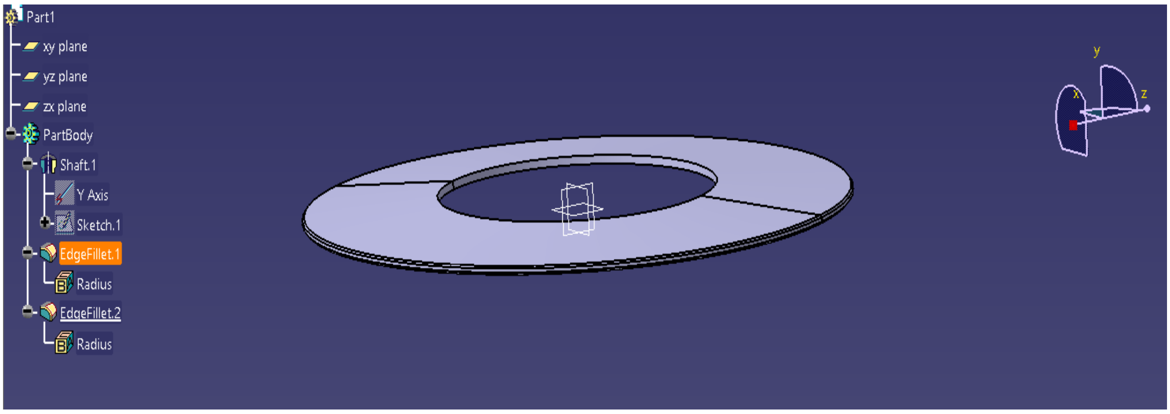


Fig. 3. 3D modeling of Belleville Spring Washer

## 5. Finite Element Analysis of Belleville Spring Washer Using Ansys14.5

ANSYS is general-purpose finite element analysis (FEA) software package. Finite Element Analysis is a numerical method of deconstructing a complex system into very small pieces (of user-designated size) called elements. The software implements equations that govern the behaviour of these elements and solves them all; creating a comprehensive explanation of how the system acts as a whole. These results then can be presented in tabulated or graphical forms. This type of analysis is typically used for the design and optimization of a system far too complex to analyse by hand. Systems that may fit into this category are too complex due to their geometry, scale, or governing equations.

Generic Steps to Solving any Problem in ANSYS:

First, Prepared Belleville Washer model in CATIA V5 and Save as this part as IGES for Exporting into Ansys Workbench 14.5 Environment. Import .IGES Model in ANSYS Workbench Simulation Module.

1. Apply Material for Belleville Washer
2. **Material Details:** H13 tool steel properties as shown in Table 1
3. Mesh the Belleville Washer
4. Define boundary condition for Analysis Boundary conditions play an important role in finite element.
5. Define type of Analysis for Belleville Washer

   **Type of Analysis:-**Static Structural
6. Apply the solution elements
7. Run the Analysis
8. Get the Results

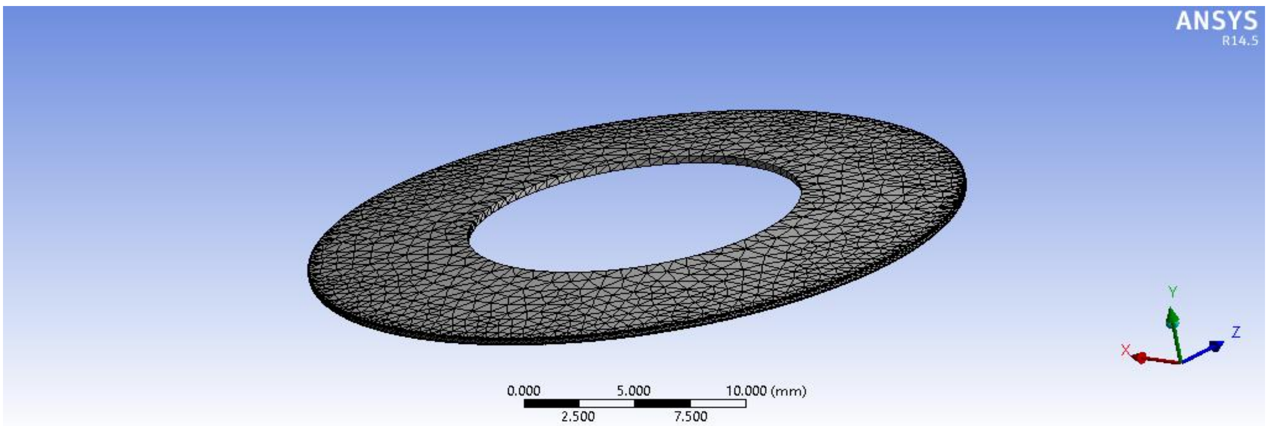


Fig. 4. Meshed model of Belleville Spring Washer

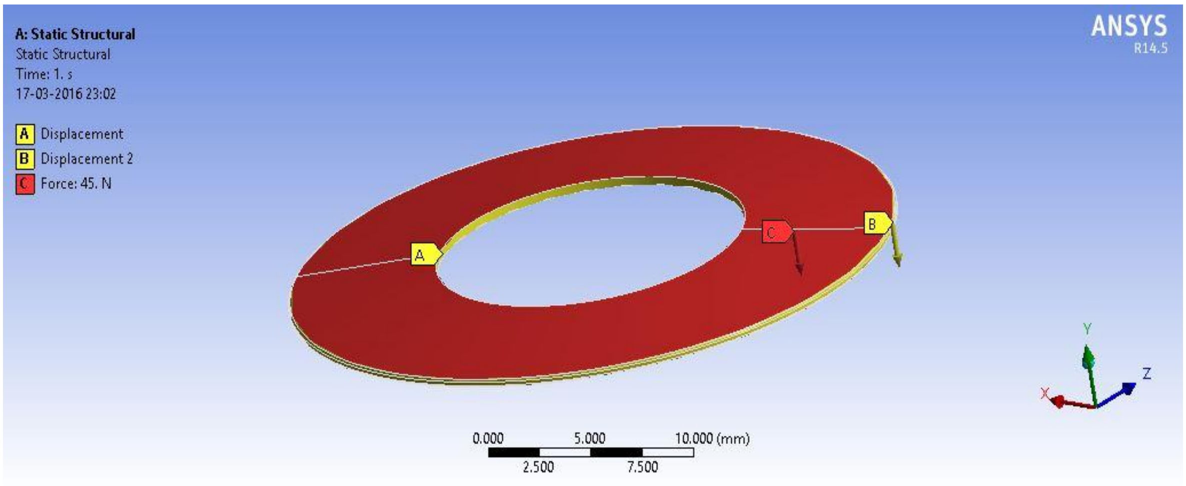


Fig. 5. Boundary conditions of Belleville Washer

## 5.1. Static Structural Analysis of Belleville Spring Washer

A static analysis calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time varying loads. A static analysis can, however. Include steady inertia loads (such as gravity and rotational velocity), and time varying loads that can be approximated as static equivalent loads. Static analysis determines the displacements, stresses, strains and forces in structures and components caused by loads that do not induce significant inertia and damping effect. Steady loading and response conditions are assumed; that is, the loads and structures response are assumed to vary slowly with respect to time [6].

In order to find out the stress distribution and deformation across a Belleville Washer, we have used ANSYS Software and results are simulated. Then the simulated results have shown the stress and deformation across the washer.

From the fig 6 it is clear that the maximum stress is the portion in red color and it is present at the inner diameter of the washer.

The above fig 7 shows that the red color part i.e. inner diameter has maximum deformation, while the blue colored part has minimum deformation and the green portion depicts intermediate deformation. Thus the simulation is over.

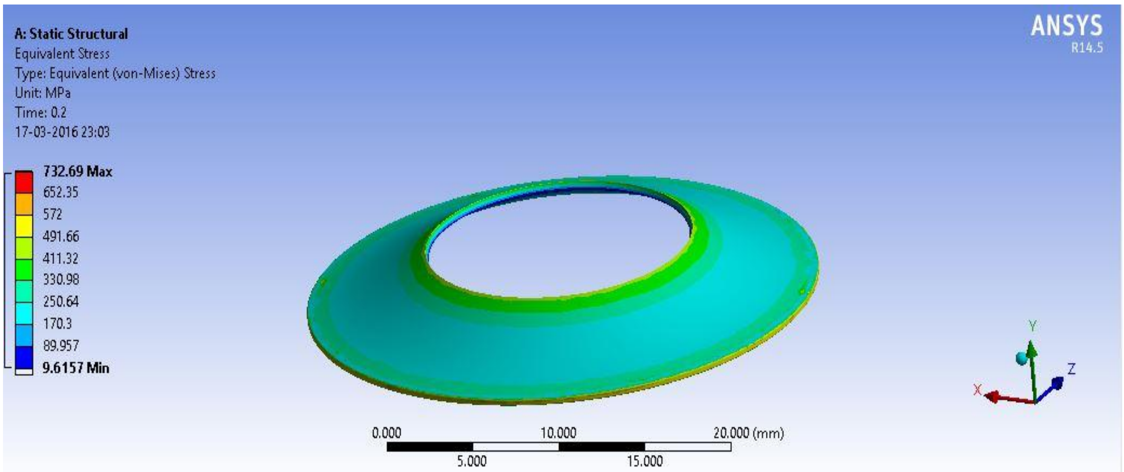


Fig. 6. Stress distribution on Belleville Washer

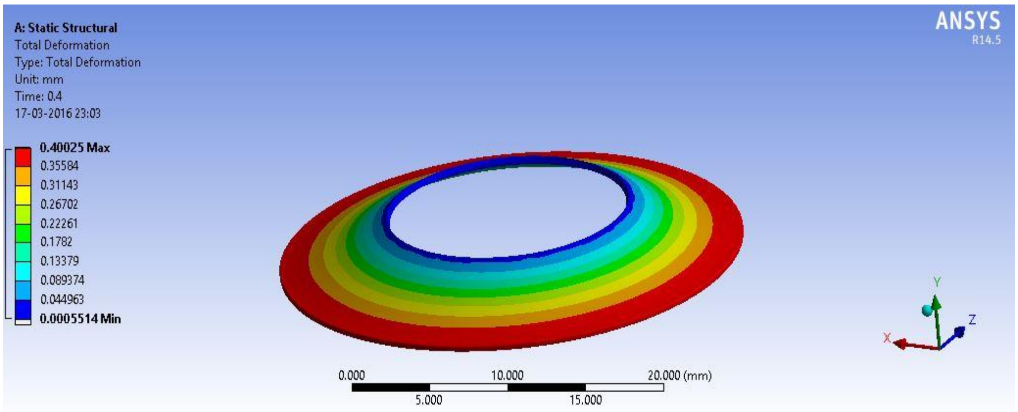


Fig. 7. Total deformation on Belleville Washer

## 6. Conclusion

- In this research, the Belleville washer spring model was created by CATIA V5R20 software. Then model was imported in Ansys 14.5 simulation software.
- In theoretical calculations we got maximum design stress as 792.27 MPa on the Belleville Washer when subjected to known load. When simulated, we get maximum von-misses stress at corresponding area as 732.69 MPa. This shows that the simulated stress Result is lower than the yield stress of tool steel material.
- The maximum deformation from theoretical approach is 0.735mm and from simulation is 0.40mm. The Theoretical Approach and Simulated results have more or less equal values, in which the Stresses are always less than the Yield Stress. Hence, the design is said to be safe
- Just by altering the height to thickness ratio, which is the key element of the design procedure, there would be drastic changes in their characteristics, enabling them in varied applications. The stacking procedure promotes these springs to the next level of usage without any change in the design.
- At last, the questions which were not addressed by the conventional springs are answered by Belleville Springs with simplicity.

## Acknowledgment

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