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A Paper on "Simulation and Analytical Model of Belleville Washer to Investigate Load-Deflection Characteristic"

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ABSTRACT: The simulation and analytical approach for compression testing of Belleville spring washers is used to investigate the load-deflection characteristicsto measure the performance of the Belleville washer during compression loading and unloading. This research aims to create an FEA model of the washer and apply boundary conditions in the simulation and also perform an analytical approach using Almen-Laszlo's theory to study the stresses and loads at the deflection specified in the selected Belleville washer. The performance of these washers is analyzed and recorded at various deflection points. At the maximum deflection of 0.6 mm, the maximum load on the upper ring of the Belleville washer is observed for during compression testing and the percentage error of the Belleville washer is calculated at each deflection. Additionally, the load-deflection curve is plotted and compared using both approaches.

Keywords- M12 Belleville washer; Load-deflection characteristics; FEA Simulation; Analytical Model.

I. INTRODUCTION

Belleville washers are also referred to as conical spring washers, disc washers, or disc spring washers. Belleville washers are produced for different types of applications such as compression, extension, and constant force. Depending on the work, a spring can be in static or dynamic condition. A Belleville washer is generally considered static and dynamic if the deflection or load changes only occur a few times. Therefore, the load-deflection characteristics, calculated using the spring equation, vary significantly from those obtained from the actual measurement. National and international standards specify the dimensions as well as the initial height of the washer. The test load is also specified for each size of the washer to verify permanent assembly. But from an application point of view, the most important data is the load that the washer exerts on the nut when the nut is screwed in to fully compress the washer. This load is responsible for providing the necessary frictional torque to prevent the assembly from loosening. The designer should calculate this force when designing a nut, bolt, and spring washer. In this work, a FEM approach will be developed and an analytical approach will also be adopted to understand its behavior in both approaches.

II. METHODOLOGY

The Methodology used in this research paper is to create an FEA Model of the M12 Belleville washer in ANSYS 2020 R1 and also creating an analytical model of the M12 Belleville washer using Almen-Laszlo's theory.

a) **Finite Element Analysis of M12 Belleville washer:** The modern technique like Finite Element based explicit dynamic analysis (ANSYS 2020 R1) is used here to determine the load-deflection characteristics of the M12 Belleville washer. This FEA simulation is also used to determine the stresses at a point defined in the theoretical approach and using the probe feature we can determine the stresses at any point in the selected washer.
b) **Analytical Approach on M12 Belleville washer:**Load-Deflection Characteristics of the M12 Belleville washer is determined theoretically using Almen-Laszlo's theory. By using this approach we are also able to calculate the stresses at the 3 points in the Belleville washer. Namely at points A,B and C as shown in figure no. 10.

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III. FINITE ELEMENT ANALYSIS

ANSYS develops and markets finite element analysis software used to simulate engineering problems. The software creates simulated computer models of structures, electronic components, or machines to simulate force, toughness, elasticity, temperature distribution, electromagnetism, fluid flow, and other attributes. ANSYS is used to determine the performance of a product with different specifications, without creating test products or running crash tests. For example, ANSYS software can simulate how a bridge will last after years of traffic, how to better treat salmon in a cannery to reduce waste, or how to design a slide that uses less material without sacrificing safety. Most of ANSYS simulations are performed using ANSYS Workbench software, which is one of the company's main products.ANSYS process comprises of preprocessing, post-processing where all the work is carried out, Use of modeling software CATIA V5R20 for modeling of Plate (Top and Bottom Plate), and M12 Belleville Washer as shown in fig 1 and 2 respectively. Firstly we have to determine few things such as Outer diameter (D), Inner diameter (d), thickness (t), Total height of the washer (H), the actual height of the washer (h) where H= h+t. For modeling of the washer, the above-mentioned parameters should be well defined and properly modeled.

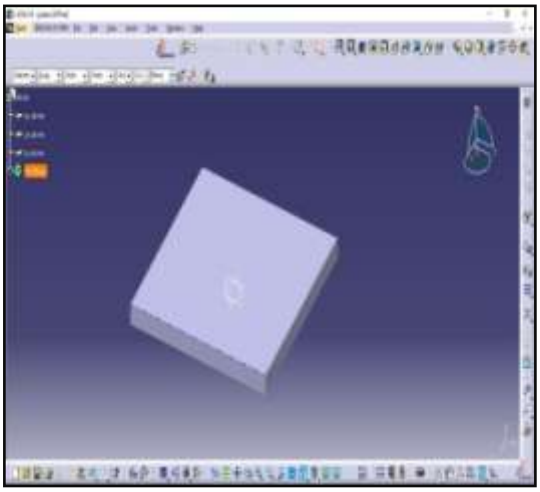

Figure 1: CATIA model of the plate

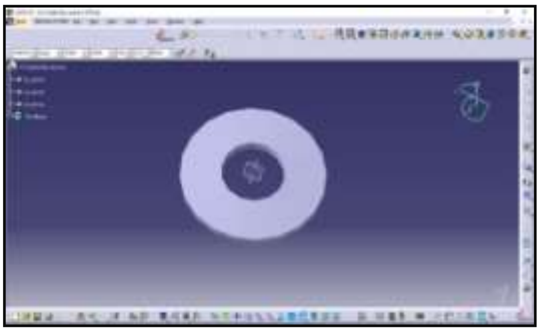

Figure 2: CATIA model of Belleville washer

But the CATIA part file cannot be directly introduced in ANSYS workbench; they need to be converted into .igs or .stp file to be accepted in the workbench. Then the workbench can carry out the pre-processing of the model such as applying fixed support to the bottom plate and displacements to the top plate.

a) **Pre-Processing:**Preprocessor Within the preprocessor the model is set up. It includes some steps and usually in the following order:

Build geometry: Depending on whether the geometry of the problem is one-dimensional, two-dimensional, or three-dimensional, the geometry consists of creating lines, areas, or volumes. These geometries can be used, if necessary, to create other geometries using Boolean operations. The key idea in building geometry in this way is to simplify the generation of the element mesh. Therefore, this step is optional but used more frequently. However, nodes and elements can only be created from coordinates. But here we have imported the geometry from CATIA V5.

Define materials:A material is defined by its material constants. Every element has to be assigned a particular material. Following were the material properties used for simulation purpose

Table 1.Mechanical Properties of the material

SN.	Material properties	Values
1	Modulus of Elasticity, N/mm^2	200000
2	Poisson’s Ratio	0.3
3	Density, kg/m^3	7800
4	Tensile strength, N/mm^2	275

Connections: Here the assemble is not bonded they are done in a dynamic explicit environment so there must be a proper definition of the contact surfaces of the body in the simulation we have to introduce the frictional contacts between the plates and washer. Following figure 3 and 4 represents the frictional contacts setting and control set to be used in simulations.

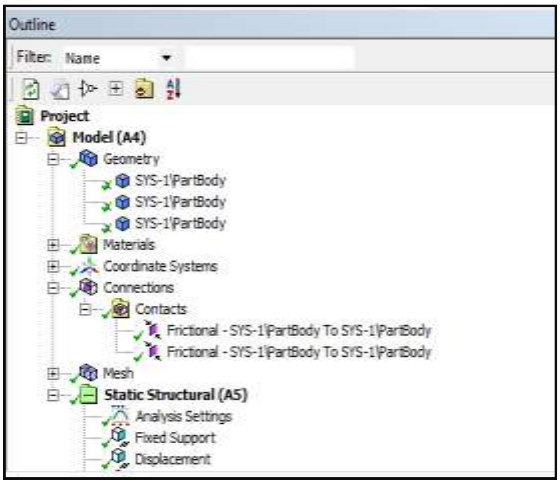

Figure 3: Representation of frictional contact setting in the ANSYS workbench.

Details of "Frictional - SYS-1\PartBody To SYS-1\PartBody"

Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	1 Face
Contact Bodies	SYS-1\PartBody
Target Bodies	SYS-1\PartBody
Protected	No
Definition	
Type	Frictional
Friction Coefficient	0.3
Scope Mode	Manual
Behavior	Program Controlled
Trim Contact	Program Controlled
Suppressed	No
Advanced	
Formulation	Program Controlled
Small Sliding	Off
Detection Method	Program Controlled
Penetration Tolerance	Program Controlled

Figure 4: Frictional Contact Setting

Generate Element Mesh: A sweep method mesh shown in fig 5 refers to the method in which a face of the volume has meshed (perhaps with high-quality quadrilateral elements) and then "swept" through the body creating a volume mesh. The body must have a topologically constant cross-section to sweep through.

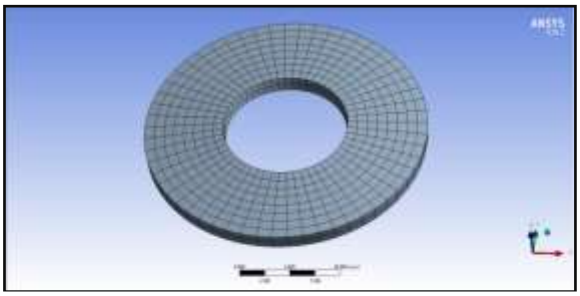

Figure 5: Mesh of Belleville washer using sweep method

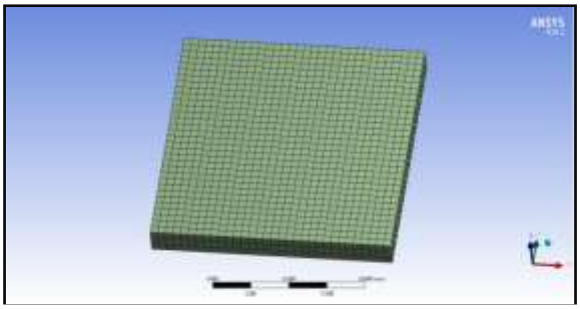

Figure 6: Mesh of the plate using the sweep method**.**

b) Solution processor: Here you solve the problem by gathering all specified information about the problem:

Apply Load: Boundary conditions are generally applied to nodes or elements. The prescribed amount can be, for example, force, traction, displacement, moment, rotation. The loads can also be changed in ANSYS by the preprocessor.

Obtain Solution: The solution to the problem can be obtained if the whole problem is defined.

c) Post- Processing: In this process, we can do the following;

Visualize the Result: For example plot the deformed shape of the geometry or stresses.

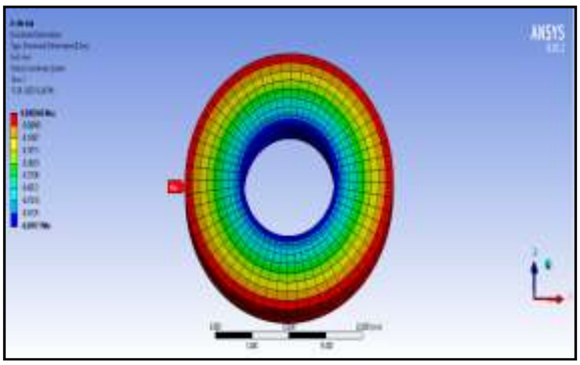

Figure 7: Deformation in M12 Belleville washer

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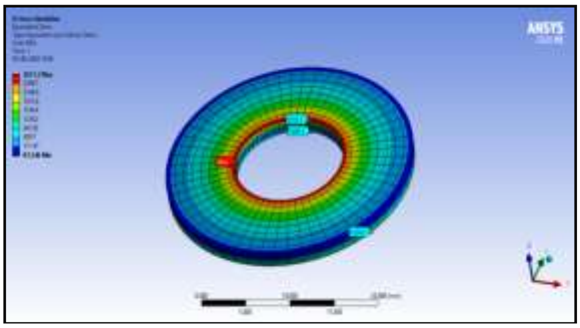

Figure 8: Equivalent Von-Mises Stress in M12 Belleville washer.

List the Result: If you prefer tabular listings or file printouts, it is possible. Stress values calculated according to the ANSYS 2020 R1 are displayed below;

Table 2.Simulation Values of Equivalent Von-Mises Stress

Stresses	Values
σ_A	2555.3 N/mm^2
σ_B	1265.5 N/mm^2
σ_C	1224.3 N/mm^2

Table 3.Simulation Values of load-Deflection

SN.	Deflection (mm)	Load (N)
1	0	0
2	0.1	407.04
3	0.2	1089.4
4	0.3	1770.7
5	0.4	2453.1
6	0.5	3135.5
7	0.6	3817.9
8	0.5	2936.2
9	0.4	2184.4
10	0.3	1576.6
11	0.2	969.42
12	0.1	362.2
13	0	1.15E-12

The load-deflection curve using the simulation approach is shown in figure no. 9, as per the research papers the maximum stress is observed at the top ring of the Belleville washer according to the simulation.

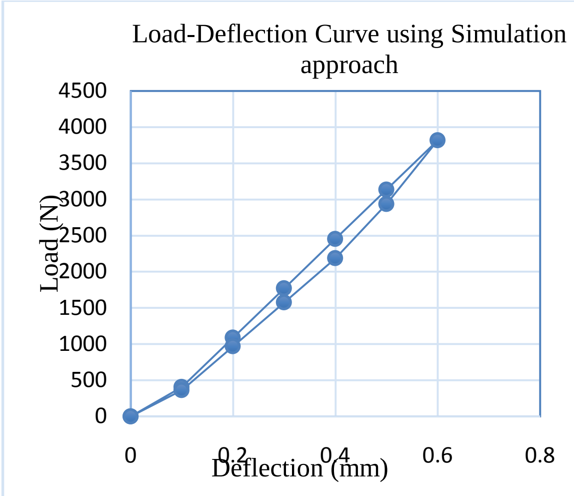

Figure 9: Load-Deflection Curve using a Simulation approach**.**

IV. ANALYTICAL BASIS

Belleville washer is conical discs of rectangular radial section normally with an Outer diameter of 8 to 250mm and they can be axially loaded from 120 to 250000N with the maximum stress on top of the inner edge at point 'A' as shown in fig 10.

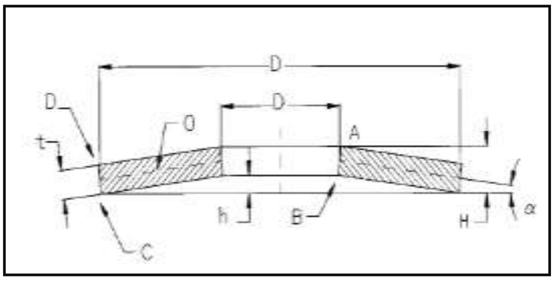

Figure 10: Schematics of Belleville washer**.**

The Belleville washers are configured to withstand maximum loads with minimum strain while storing a large amount of energy with space they occupy. They can attend flattened shape when s=h without being permanently deformed or fractured, so the following condition should be satisfied.

$s \leq 0.75h$ ……..(1)

Since Belleville washers are individually very stiff they can be stacked in parallel/series assemblies to provide them with desired elastic properties. The calculations are based on Almen-Laszlo Theory, which is approximate and holds good in actual practice. We can express the following relation between stress and deflection as

$$\sigma_{A} = -\frac{4Es}{(1-v^2)C_3 OD^2}\left[C_1(h_0 - 0.5s) + C_2 t\right]$$

……(2)

$$\sigma_{B=} -\frac{4Es}{(1-v^2)C_3 0D^2}[C_1(h_0 - 0.5s) - C_2 t] \quad …….(3)$$

$$\sigma_{C=} -\frac{4Es}{(1-v^2)0D^2}[T_1(h_0 - 0.5s) + T_2 t] \quad ……(4)$$

Where

$$C_1 = \frac{6}{\pi \ln\gamma}\left\{\frac{\gamma-1}{\ln\gamma} - 1\right\} \qquad T_1 = \frac{\gamma\ln\gamma - (\gamma-1)}{\ln\gamma} * \frac{\gamma}{(\gamma-1)^2}$$

$$C_2 = \frac{6}{\pi \ln\gamma}\left\{\frac{\gamma-1}{2}\right\}$$

$$C_3 = \frac{6}{\pi \ln\gamma}\left\{\frac{(\gamma-1)^2}{\gamma^2}\right\} \qquad T_2 = \frac{\gamma}{2(\gamma-1)}$$

…..(5)

Where C_1,C_2,C_3,T_1, and T_2 are Compression stress and Tensile Stress constants respectively.

For calculating the load at a certain value of displacement and also to provide attend equilibrium at that instant of displacement following relation is used:

$$F = \frac{4Est}{(1-v^2)C_3 0D^2}[(h_0 - s)(h_0 - 0.5s) + t^2] \quad ……(6)$$

But for flattening position above equation is transformed in the below equation

$$F' = \frac{4Et^3h_0}{(1-v^2)C_3 0D^2} \quad ……(7)$$

Stress values of the Belleville components are calculated by Almen-Laszlo's theory and are displayed in table no. 4. Whereas in table no. 5, load at a specified deflection is obtained using the Analytical approach, further the load-deflection curve for the Analytical approach is shown in figure no. 11. It is observed that the Stress values using both the approach are approximately close. Whereas it is observed that the load-deflection values are good at the highest point of deflection in this research whereas at the starting point of deflection (i.e. at 0.1 mm) the values of both the approaches are considerably large.

Table 4. Analytical Values of Equivalent Stress

Stresses	Values
σ_A	2575.84 N/mm^2
σ_B	1385.84 N/mm^2
σ_C	1258.66 N/mm^2

Table 5. Analytical Values of load-Deflection

SN.	Deflection (mm)	Load (N)
1	0	0
2	0.1	736.01
3	0.2	1421.9
4	0.3	2064.9
5	0.4	2672.08
6	0.5	3250.6
7	0.6	3807.72
8	0.5	3250.6
9	0.4	2672.08
10	0.3	2064.9
11	0.2	1421.9
12	0.1	736.01
13	0	0

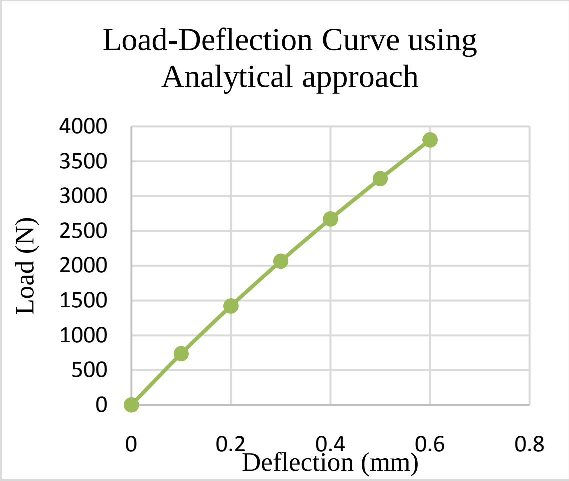

Figure 11: Load-Deflection Curve using Analytical Approach**.**

V. RESULTS AND DISCUSSION

In summary, it can be said that a series of analytical and FEM models have been designed and developed to determine the load-deflection characteristics of Belleville washer. Here are the main results of the research carried out for the loading and unloading of the M12 Belleville washer.

a) This work focuses on creating a simulation model and mathematical formulation to obtain the load-deflection characteristics of Belleville washer during compression loading and unloading.
b) In the current research, the performance of individual Belleville M12 washers is measured using the simulation and analysis approach. The results of 0.6mm bending load-deformation in the analytical method are 3807.72N, and the

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simulation method of 0.6mm bending load value is 3817.9N.

c) A minimum percentage error of 0.267% was observed in the deformation of 0.6 mm while the maximum percentage error of 50.78% was observed in deformation of 0.1 mm under conditions of the discharge as indicated in table no. 6.

d) The stresses obtained in the simulation approach and the analytical approach at point "A" are 2555.3 N / mm^2 and 2575.84 N / mm^2; At point "B", 1265.5 N / mm^2 and 1385.84 N / mm^2; And at point "C" 1224.3 N / mm^2 and 1258.66 N / mm^2 respectively according to the table no. 7

Table 6. Load obtained through Ansys simulation and Analytical approach with percentage error at each point.

SN.	Deflection (mm)	Analytical Load (N)	Simulation Load (N)	Percentage Error (%)
1	0	0	0	0
2	0.1	736.01	407.04	44.69
3	0.2	1421.9	1089.4	23.38
4	0.3	2064.9	1770.7	14.25
5	0.4	2672.08	2453.1	8.22
6	0.5	3250.6	3135.5	3.54
7	0.6	3807.72	3817.9	0.267
8	0.5	3250.6	2936.2	9.67
9	0.4	2672.08	2184.4	18.27
10	0.3	2064.9	1576.6	23.64
11	0.2	1421.9	969.42	31.82
12	0.1	736.01	362.2	50.78
13	0	0	1.15E-12	0

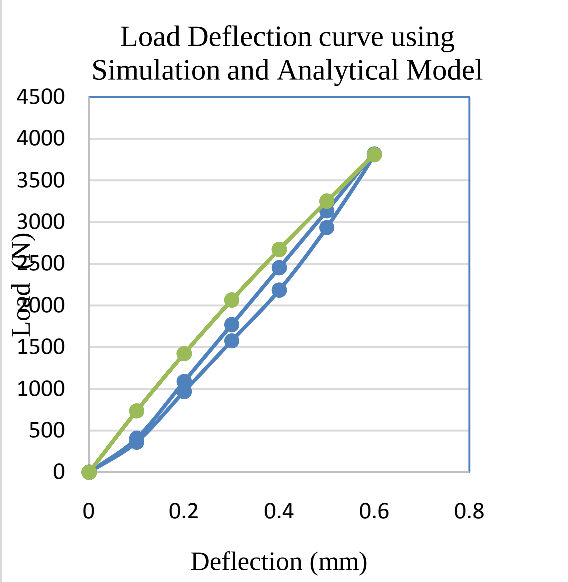

Figure 12: Load-Deflection Curve using Simulation and Analytical Approach

Table 7. Simulation and Analytical Values of Equivalent Stress

Stresses	Values	Values
σ_A	2575.84 N/mm^2	2555.3 N/mm^2
σ_B	1385.84 N/mm^2	1265.5 N/mm^2
σ_C	1258.66 N/mm^2	1224.3 N/mm^2

VI. CONCLUSION

In this investigation, we worked to study the load-deformation characteristics of Belleville washers during compression loading and unloading using simulation and analysis approaches. In a simulation, various factors such as modulus of elasticity, Poisson's ratio, mesh type, mesh size, and boundary conditions are important to obtain more accurate load-deformation data. A proper selection of these parameters is essential. The analytical approach requires a deep knowledge of the Almen-Laszlo theory, of the constants of his theory, of the load equations, and finally of the stress equations; because it may have been invented in 1936 but it still holds for this spring washer. It is easy to see that the maximum difference between the load readings is at beginning and end (i.e. 0.1mm deviation) of the loading and unloading procedure when comparing the two approaches. And also it is observed that the stress readings at points A and C have approximate or very close results in both approaches but at point B the difference in readings is relatively greater that the rest of the points in both approaches.

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