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Design and Analysis of Single Angle Expanding Collets

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Abstract

The subject of production deals with the use of fixtures that ensures repeatability to the work piece to be manufactured. The fixture is clamping device that mounts parts at a perfect location and gives stability, which leads to mass production. Thus types of clamping play a decisive role in getting the good reliability of the product. Collet is one of the clamping devices which have long slits around its periphery, widely used for clamping any kind of shape (cylindrical, hexagonal, and square etc.) in manufacturing industries. As there is an increase in demand for mass production and accuracy of parts being made, use of collet is also increased. This research paper is about determining deflection and clamping force required for collet to clamp an object. To find this, one needs to find elastic deformation of an object by deriving mathematical model and by using software tools. Formulation of the mathematical model and its solution is carried out. Deflection and clamping force is found. The mathematical model determines the elastic deformation analytically while finite elemental analysis using software tools validates the analytical design. There is a greater match between the results given by analytical method and FEA. Finite element analysis is carried out using ANSYS and MATLAB code is used to solve second order differential equation.

Keywords: *Expanding collets, design, analysis, Euler's beam theory, friction*

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INTRODUCTION

Taking the concept of flexible manufacturing system regarding manufacturing industries, fixtures are used to clamp parts at the exact location. Collet is also a clamping device which is used to clamp parts with ease. The periphery of the cylindrical surface of the collet is divided into slits called as a jaw of the collet. These jaws can expand or collapse according to the application of collet.

Collet can mount parts of any shape like a square, circular or hexagonal etc. There are mainly two kinds of collets: 1. Expanding collets, and 2. Collapsing collets. These main types are further divided into push type, pull type and multiple position type collets. According to the opening angle of the collet, it can be the single angle or double angle [1].

The collet assembly is made of collet, mandrel and puller rod. When pulling force is applied by puller rod, the expander will push the mandrel in the direction of force, as there is a taper on the surface of the collet, the collet will expand and clamp the part which is on its surface [2].

LITERATURE REVIEW

The growing need of mass production and accuracy of parts being made, with the usage of minimum resources is the key to the growth of any industry. The primary function of a collet is to hold a workpiece tightly and provide maximum accuracy to the part. As an importance, while holding workpiece tightly, parts should not deform due to high clamping force and it should not be loose at the same time. So, to provide optimum clamping force is of major importance. This research work is concentrated for the internal expanding collet.

Various literatures have been reviewed regarding friction theory, finite element analysis and Euler's beam theory. The mathematical model shows how the object originally works using principles of science and it is the representation of the performance of the object. Working on any system, basically depends on the mathematical relation among parameter influences the system. The same logic can be applicable to the internal expanding collet also. A mathematical model for the gripping force for the internal expanding collet depends on the taper angle of the collet, friction characteristic of the taper and collet and the direction in which the clamping force is acting [3]. To define a formula for the clamping force, one needs to know the basic theory of friction, which would be helpful to find the clamping force using the coefficient of friction of mating surfaces. Friction characteristic of the surface depends on coefficient of friction, which is highly sensitive to geometry and topography of the workpiece, adhesion and present of debris. Deiab and Elbestawi determined the coefficient of friction for the workpiece fixture contact in work holding application using friction characteristic of the surface. By this research, it has been found that coefficient of friction decreases as there is an increase in clamping force because of nature of surface [4]. In the case of study related to friction, the surface roughness is more important and it depends on the spindle speed, feed rate and characteristic of the surface [5].

Kumar *et al.* proposed same study for the surface roughness of five different carbon alloy steels for the variation in feed rate and spindle speed and they revealed that as there is increase in feed rate and spindle speed, surface roughness will be increased and decreased respectively. A theory of the action of a collet has been developed by Mcllraith, it uses friction to explore the dependence of the firmness of grip, the ease of release and the interface stresses on the cone angle, the interface coefficients of friction and the applied axial forces [6]. When we apply force to the slits of collets through puller rod and mandrel, slits of collet will deformed. This deformation analysis of slits of the collet is carried out by Soriano *et al.*, who took collet jaw as a cantilever beam and determined the static stiffness of collet sleeves [7]. In another research by Joshi and Patel, each jaw of the collet is taken as a cantilever beam and deflection of the collet is obtained [8].

During machining of any object, various forces act on it. An internal expanding collet also undergoes various forces due to machining. These unbalanced forces are the primary reason for the vibration and stress in the object. To find these stresses and deformation of the object due to stresses, one of the reliable methods is the finite element analysis. This method gives us stress at each element and local deformation of the element in an object. Finite element analysis not only gives the local stress and elastic deformation of an object but also provides key information for the weak part of an object, from where it may break. Finite analysis of a flexible collet is done by Lv *et al.* for finding local stress and elastic deformation. They have provided guidelines for making finite element modelling [9]. The method of finite element analysis provides the basic information for the workpiece deformation due to stress setup under loading condition and it also provides the amount of deformation so that we can give tolerances for an object. So, if we can predict the deformation of an object under loading condition, then it would be easier for an engineer to setup the tolerances for the mating parts.

This kind of study is done by Shane *et al.* They found that the locators generate reaction forces during machining and these forces are also responsible for workpiece deformation with the machining forces. Results of this experiment are validated by the experimental setup and having about 95% accuracy with the FEA [10]. Study of Satyanarayana and Melkote also supports a theory for deformation of the workpiece by reaction forces and machining forces. They have analyzed workpiece for different boundary conditions [11]. Deformation analysis of a fixture workpiece is carried out by Wang *et al.*, and found that in a dynamic condition, workpiece and locators are sliding relative to each other. They also found that major source of error in deformation is due to the layout of fixture [12].

From this research study, it is clear that deformation of an object during machining condition depends on various parameters like the layout of locators, machining condition, reaction force by locators. Not these only, clamping sequence also affects the part location in the fixture workpiece element system. Effect of clamping sequence is examined through simulation and experimental setup for finding possible location errors [13]. This research study can be useful in making clamping of the part in fixture quick and accurate. So, from the study of various literature, it has been found that design of collet deals with the characteristic of surface roughness and the amount of amplification required for gripping of an object. As the amplification-clamping force deforms slits of the collet, it is required to determine the amount of deformation. So, the study of these literatures shows that there is no significant work done in the field of design of collet.

Objectives of Research

This research study is carried out based on following objectives:

1. To determine the clamping force and deflection of collet;
2. To determine the reaction of force; and
3. To evaluate deflection and reaction of force.

Statement of Problem

- To determine the clamping force and deflection of the single angle expanding collets by using basic principles.
- Validation of findings using FEA by frame elements and by using FEA solver as ANSYS.

ANALYTICAL DESIGN OF SINGLE ANGLE EXPANDING COLLET

Analytical design of single angle expanding collets is carried out using predefined fundamental concepts of applied mechanics and working of internal expanding collets.

Friction theory is used to determine the amount of clamping force and Euler's beam theory is used to form equation for determining the amount of deformation. This deformation in the form of second order differential equation is then solved using MATLAB code.

Model of Collet

A model of collet is prepared using Creo 2.0. The collet is cut into some slots and made of 12 jaws.

The collet is made up of EN24 steel isotropic material. A 3D, 2D CAD model and sectional views of the collet are shown in Figures 1–4.

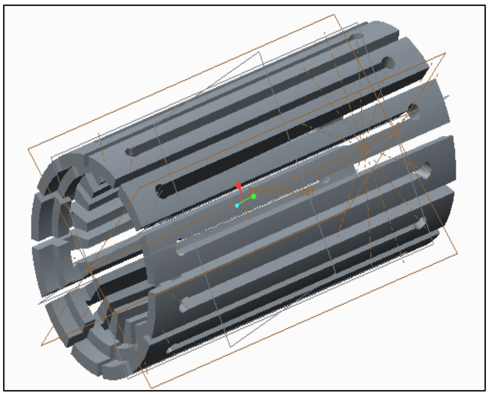


Fig. 1: *3D CAD Model of Collet.*

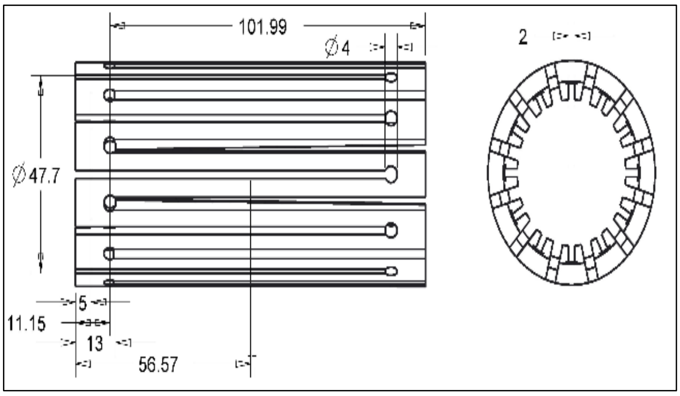


Fig. 2: *2D CAD Model of Collet.*

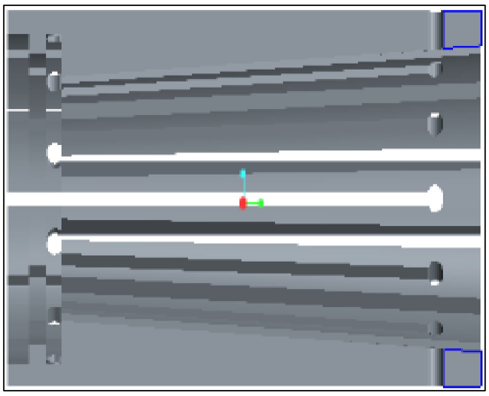


Fig. 3: *Sectional 3D View of Collet.*

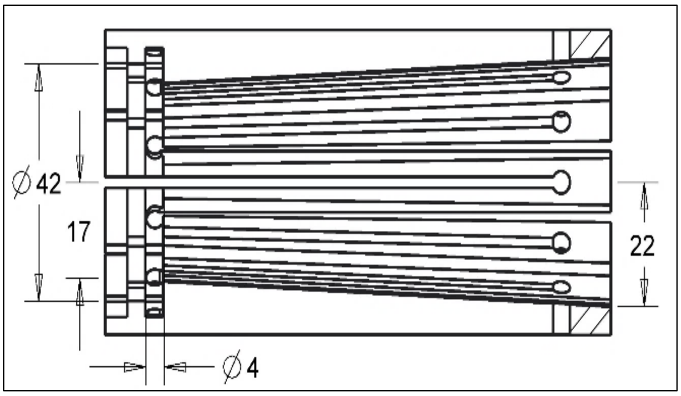


Fig. 4: *Sectional 2D View of Collet.*

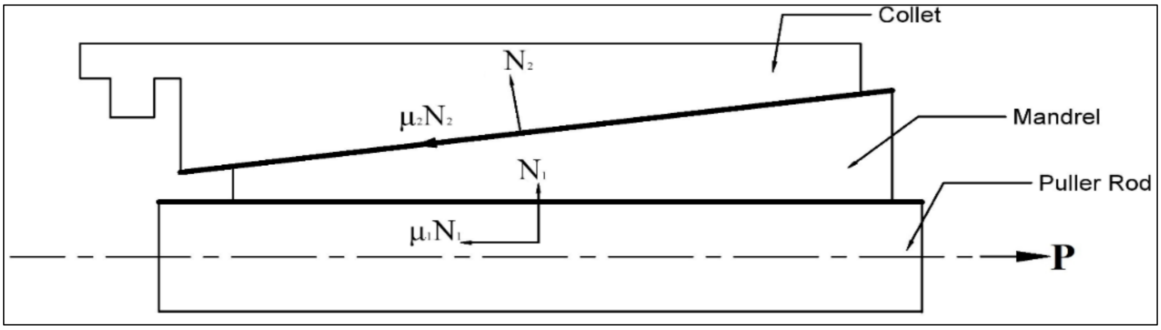


Fig. 5: *Collet, Mandrel and Puller Rod System.*

Friction Theory

The basic working of internal expanding collet shows that the collet assembly is comprised of the mandrel, puller rod, and collet [2]. When pulling force is applied by puller rod, the expander will push the mandrel in the direction of force, as there is a taper on the surface of the collet, the collet will expand and clamp the part which is on its surface The mandrel is having contact with both, collet and puller rod, so, when we have the dynamic condition, these contacts will have friction (Figure 5). Mcllraith derived relations among parameters for finding clamping force by the theory of friction in his research study, so, we can use the theory of friction for finding clamping force [6].

The theory of friction can be applicable to the assembly of the collet [6]. So, when we have known value of pulling force (P), we will be able to find clamping force (N).

Assuming the collet is made of n number of slits, so, we can write:

$N_2 = n * N$

From Figure 5, when we resolve forces horizontally,

$P = \mu_1 N_1 + \mu_2 N_2 \, cos(\alpha) + N_2 sin(\alpha)$

When we resolve forces vertically,

$N_1 = N_2 \cos(\alpha) - \mu_2 N_2 \sin(\alpha)$

Considering above equations, we will have:

$$P = N_2((\mu_1 + \mu_2)\cos(\alpha) - (1 - \mu_1\mu_2)\sin(\alpha))$$

Where,

N_1= Normal force because of friction between mandrel and puller rod,

N_2= Normal force because of friction between mandrel and the collet,

α= Angle of taper =2.85^0,

n= Number of slits =12,

P= Pulling force =1000 N (Assumed),

μ_1= Coefficient of friction of mating surface between puller rod and mandrel =0.33 (Assumed),

μ_2= Coefficient of friction of mating surface between mandrel and the collet =0.33 (Assumed).

$\boldsymbol{N_2} = \mathbf{1410.62}$ **N**

$\boldsymbol{N} = \mathbf{117.55}$ **N**

As we have taken half of slit of the collet, available clamping force for the analysis would be 58.78 N.

Slit of Collet as a Simply Supported Beam

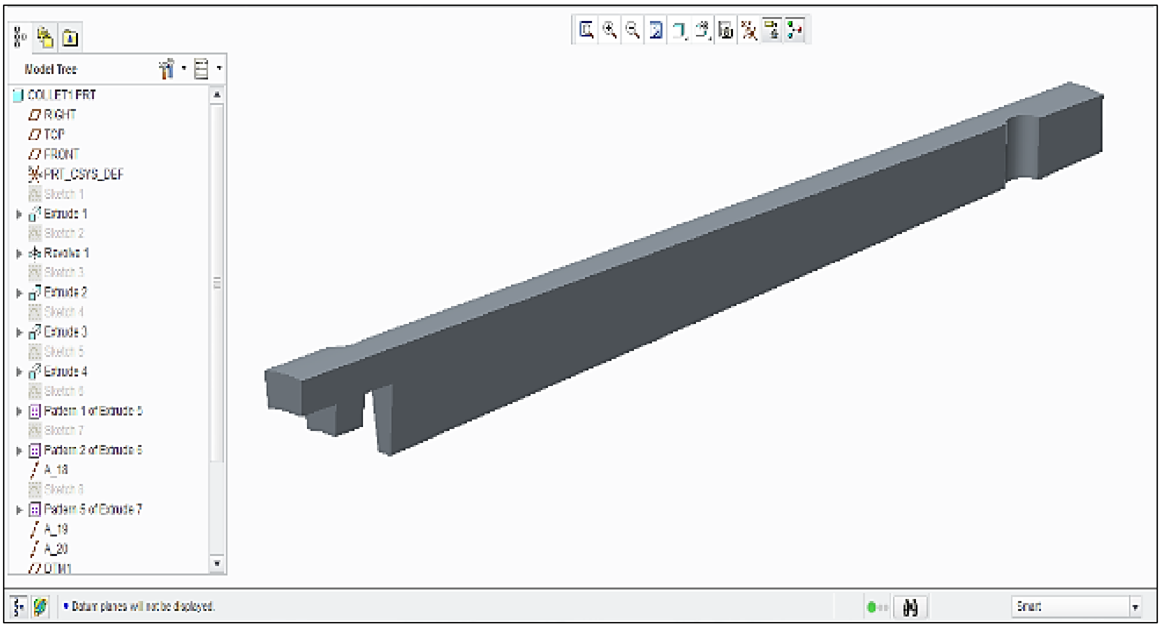
In this section, we will determine the amount of deformation because of clamping force. In one research study by Joshi and Patel, each jaw of the collet is taken as a cantilever beam and deflection of the collet is obtained [8]. Here, to determine the amount of deformation, we will take half slit of collet (Figure 6) as a simply supported beam. To find deflection for tapered simply supported beam, we will use Euler’s beam theory.

Figure 7 shows the non-prismatic simply supported beam having uniform loading (N) over its length (L). The angle of internal taper is α, the thickness of beam is sectorial 2θ and width of the beam is R_x. The material of the collet is EN24 is isotropic with modulus of elasticity as E=200000 Nmm^{-2} [14].

As the beam is considered as simply supported, deflection at the ends will be zero. Euler beam theory can be applicable to find the deflection of selected beam [8]. To find the deflection, we can use the equation of deflection;

$$\frac{d^2y}{dx^2} = \frac{M_x}{I_g * E} \qquad (1)$$

To solve above equation for the deflection, we need to find bending moment about C.G. axis and area moment of inertia about C.G. axis.



• Datum planes will not be displayed.

Fig. 6: *Creo Model of Half Slit of Collet.*

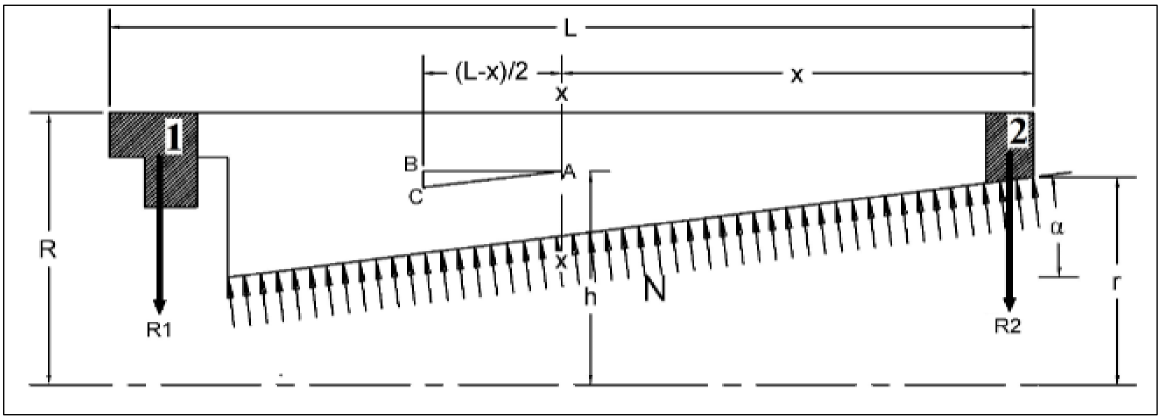


Fig. 7: *Collet as a Simply Supported Beam.*

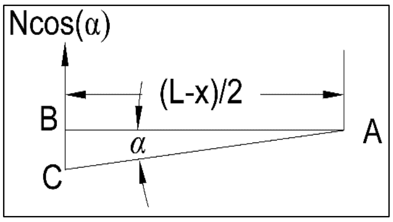


Fig. 8: *Analyzed Triangle.*

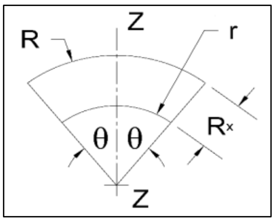


Fig. 9: *Sector of One Slit of Collet.*

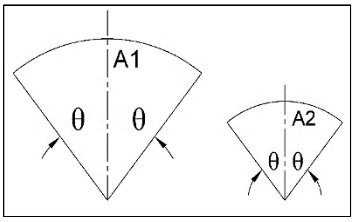


Fig. 10: *Area of Sector of Collet Slit.*

Considering Figures 7 and 8, bending moment M_x at section X-X will be;

$$M_x = \frac{Ncos(\alpha) * (x+L)}{2*L} * \frac{L-x}{2}$$

From Figures 9 and 10, area moment of inertia I_g about C.G. axis [8];

$$I_g = \frac{\left(\theta+\frac{\sin(2\theta)}{2}\right)\left(R^4-(R_x)^4\right)}{4} - \frac{4\left(\sin(\theta)\left(R^3-{R_x}^3\right)\right)^2}{9\theta\left(R^2-{R_x}^2\right)}$$

Here, assuming2θ = Angle of sector of slit = 15^0,$R_x = R - r + (x * \tan(\alpha))$, $R = 27\ mm, r = 22\ mm, \alpha = 2.85^0$

Now, Euler's equation for finding deflection of beam;

$$\frac{d^2y}{dx^2} = \frac{\frac{Ncos(\alpha)*(x+L)}{2*L} * \frac{L-x}{2}}{\left(\frac{\left(\theta+\frac{\sin(2\theta)}{2}\right)\left(R^4-(R_x)^4\right)}{4} - \frac{4\left(\sin(\theta)\left(R^3-{R_x}^3\right)\right)^2}{9\theta\left(R^2-{R_x}^2\right)}\right)*E}$$

Solution of Deflection using MATLAB

As we see that the Euler's equation for finding deflection contains the second order with values of x in numerator and denominator, it is very difficult to find it using elementary numerical solution method manually. So, MATLAB solver is used for solving second order differential equation of deflection.

MATLAB Code;

```
>>syms y(x)
>>F=58.78;
>>l=113.14;
>>t=0.049741883;
>>t1=0.130899693;
>>R=27;
>>r=22;
>>E=200000;
>>M=((F/l)*(l+x)*(1/2))*cos(t)*(((l-x)/2));
>>I=(((sin(2*t)/2+t)*(1/4)*((R^4)-(r-
(x*tan(t1)))^4)))-
((4/9)*(1/t)*(sin(t)^2)*((R^3)-(r-
(x*tan(t1)))^3)*(1/((R^2)-(r-(x*tan(t1)))^2)));
>>A=M/(I*E);
>>Dy=diff(y,x);
>>y(x)=dsolve(diff(y,x,2)==A,y(9.5)==0.0002
503498463,Dy(0)==0.0002503498463);
>>ymax=double(y(56.57))
ymax=0.0134+0.0000i
```

The second order differential equation is solved using MATLAB code. It shows the maximum deflection at the midspan of the beam and its value is 0.0134 mm. From this MATLAB code, we can find out deflection at any arbitrary length of the beam.

VALIDATION OF ANALYTICAL DESIGN

In this section, the deformation of the collet is analyzed using FEA by frame elements and analysed in ANSYS workbench. In FEA by frame elements, six elements with seven nodes and in ANSYS, analysis is done using hexagonal dominant method and mesh size is restricted to 0.5 mm, 117347 nodes and 27389 elements were created.

FEA by Frame Elements

Finite element analysis can be used to find deflection [9]. The elements are having three DOF and six elements are taken for the analysis. It has been seen that as we increase number of elements, there will be increase in accuracy of results but that requires a number of computations and time [15]. The stiffness matrix is derived using theory for frame elements [16].

Area moment of Inertia =2517.64425 mm^4;

Modulus of Elasticity =200000 Nmm^{-2}

Table 1: *Element Properties.*

Element Properties	**Element 1**	**Element 2**	**Element 3**	**Element 4**	**Element 5**	**Element 6**
C/s Area (mm^2)	21.8	21.5	24.4	26.7	28.4	23.4
Length of Elements(mm)	13.5	23.535	23.535	23.535	23.535	13.5

From above element properties (Table 1), we can find stiffness matrix for each element and from stiffness matrix of each element, we can form global stiffness matrix of rank 21. To find the deflection, we need to find out the load on each node. As given load on the slit of the collet is UDL, we need to divide load into seven equal divisions because each node shares the same load. The loading matrix for the each element is to be calculated and then combining cell addresses we can form global load matrix. Multiplication of inverse of global stiffness matrix and global load matrix will give the value of deflection (Figure 11).

$[K]^{-1} \times [F]=[D]$

Here we can see that amount of deflection is 0.0133 mm.

ANSYS Workbench Analysis

The force which is given by the workpiece to the collet is the reaction force regarding collet. Here, the maximum deflection occurs at the mid-span of the beam, so the reaction of force will be calculated at the mid-span of half slit of the collet. In the previous section, we have calculated reaction of force by analytical method, in this section, reaction of force is found using ANSYS workbench. ANSYS workbench analysis is carried out for finding the amount of deformation. Modelling is done using Creo 2.0 and then the model is imported into ANSYS workbench (Figure 12). Material for the collet is EN24 steel, so properties of the same are used.

Properties [16]:

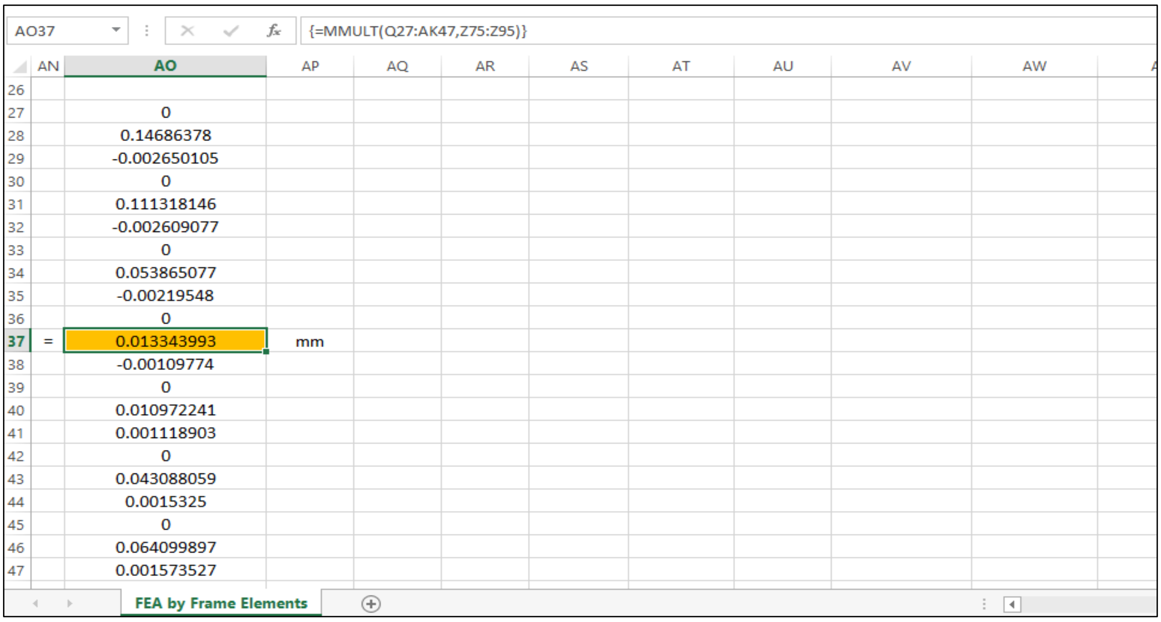
Modulus of Elasticity =200000 Nmm^{-2}

Density =8.17 gm/cc

Poison's Ratio =0.33

Tensile Strength =850 Nmm^{-2}

Yield Strength =650 Nmm^{-2}

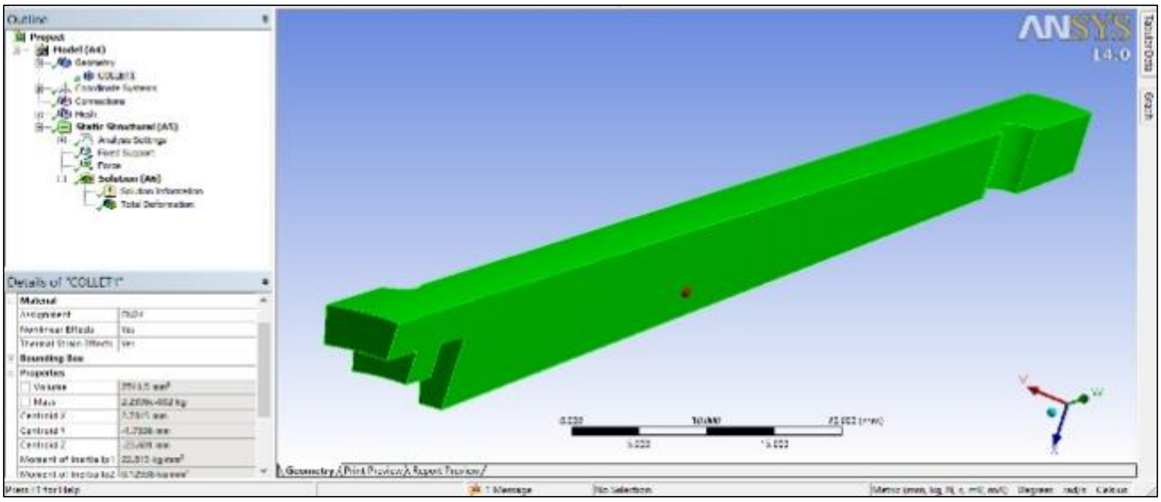


AO37 {=MMULT(Q27:AK47,Z75:Z95)}

	AN	AO	AP
26			
27		0	
28		0.14686378	
29		-0.002650105	
30		0	
31		0.111318146	
32		-0.002609077	
33		0	
34		0.053865077	
35		-0.00219548	
36		0	
37	=	0.013343993	mm
38		-0.00109774	
39		0	
40		0.010972241	
41		0.001118903	
42		0	
43		0.043088059	
44		0.0015325	
45		0	
46		0.064099897	
47		0.001573527	

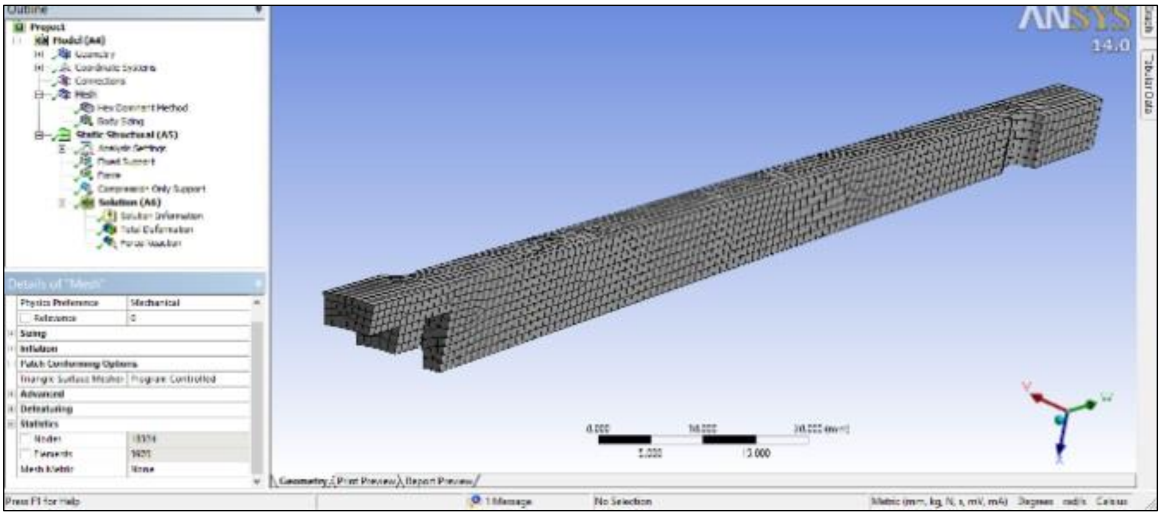
FEA by Frame Elements

Fig. 11: *Result of Deflection.*



Details of "COLLET1"

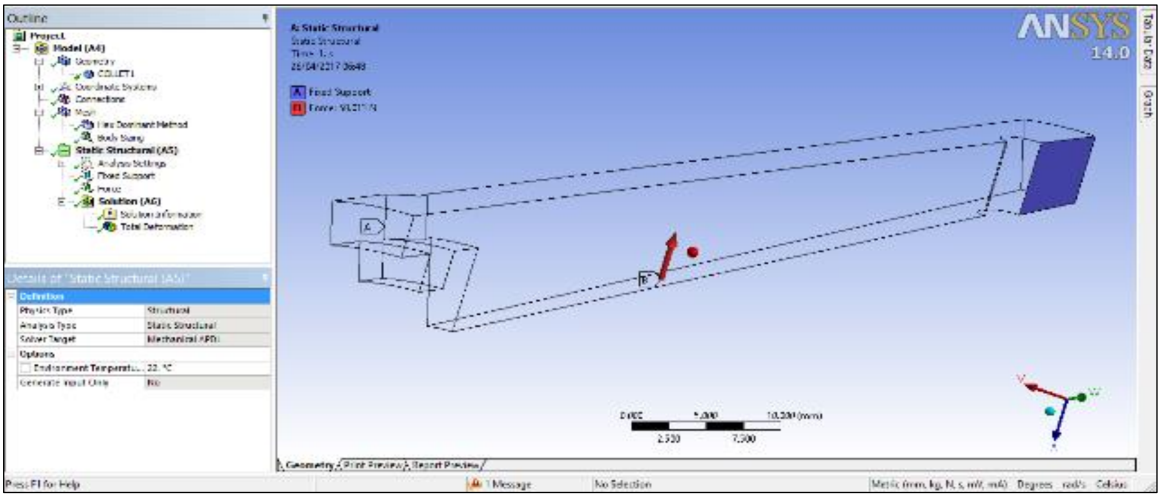
Fig. 12: *Model of Half Slit of Collet.*



Details of "Mesh"

Physics Preference: Mechanical
Triangle Surface Mesher: Program Controlled
Mesh Metric: None

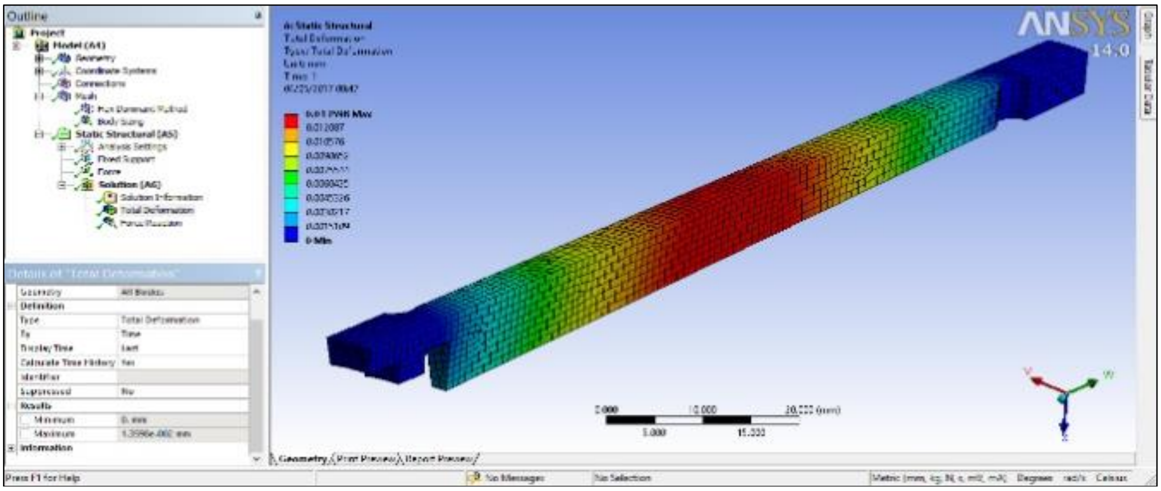
Fig. 13: *Meshing Condition.*



Details of "Static Structural (A5)"

Definition	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperatu...	22. °C
Generate Input Only	No

Fig. 14: *Boundary Conditions.*



Details of "Total Deformation"

Geometry	All Bodies
Definition	
Type	Total Deformation
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No
Results	
Minimum	0. mm
Maximum	1.3596e-002 mm
Information	

Fig. 15: *Result of Deflection.*

Table 2: *Comparison of Different Methods of Finding Deflection.*

Sr. No	Method	Deflection Maximum (mm)	Difference (mm)	Difference (%)
1	Analytical Approach	0.0134	-	-
2	FEA by Frame Elements	0.0133	0.0001	0.74%
3	ANSYS Workbench	0.0136	0.0002	1.47%

Comparison of Various Methods of Finding Deflection

In this section, we have compared results obtained from various methods for finding deflection. We have compared the analytical approach of finding deflection, where we have used MATLAB code to solve second order differential equation, FEA by frame elements and ANSYS workbench (Figure 13-15).

Study of these results shows that there is the greater match of results. From Table 2, we can see that the difference between results through various methods is nearer. So, we can conclude that method of using Euler's beam theory for single angle expanding collet is valid.

DETERMINATION OF REACTION OF FORCE

In the present study, we will be determining the reaction of force given by the workpiece to the collet while clamping. We already found the amount of clamping force using theory of friction, so when we find the reaction of force, by the third law of Newton, the amount of reaction should be same as that of clamping force. So determining the reaction of force, we have taken a half slit of collet as a simply supported beam (Figure 16).

Here, we will first determine the reaction of force analytically and then it will be compared with results of ANSYS workbench.

Here assuming,
α= Angle of taper of collet =2.85^0
L= Length of collet =113.14 mm
N= Normal force to the slit of collet =58.78 N

Step 1: To Determine Reaction of Force at the Center of Span

To find the reaction of force at the mid-span of half slit of the collet, we need to consider the half slit of collet as a tapered simply supported beam. The force of clamping is calculated as;

$$N_c = Ncos(\alpha) = 58.78 * cos(2.85)$$
$$= 58.71\,N$$

Step 2: To Find Reaction of Force at the Supports

From Figure 14,
$R_1 + R_2 = 58.71\,N$
Taking moment at support 2,
$N_c * L/2 = R_1 * L$
$R_1 = (N_c)/2 = 58.71/2 = 29.355\,N$
$R_2 = 58.71 - R_1 = 58.71 - 29.355$
$= 29.355\,N$
So, reactions of force at supports are:
$R_1 = R_2 = 29.355\,N$

Validation of Reaction of Force by ANSYS Workbench

The force which is given by the workpiece to the collet is the reaction force regarding collet. Here, the maximum deflection occurs at the mid-span of the beam, so the reaction of force will be calculated at the mid-span of half slit of the collet. In the previous section, we have calculated reaction of force by analytical method, in this section, reaction of force is found using ANSYS workbench. So, the results from the analytical method are compared with results of ANSYS workbench. If results of both methods match, then it proves that we can use defined analytical method widely. ANSYS workbench analysis is carried out for finding the amount of deformation. Modelling is done using Creo 2.0 and then the model is imported into ANSYS workbench (Figure 17-18). Material for the collet is EN24 steel, so properties of the same are used.

Properties [16]:
Modulus of Elasticity =200000 Nmm^{-2}
Density =8.17 gm/cc
Poison's Ratio =0.33
Tensile Strength =850 Nmm^{-2}
Yield Strength =650 Nmm^{-2}

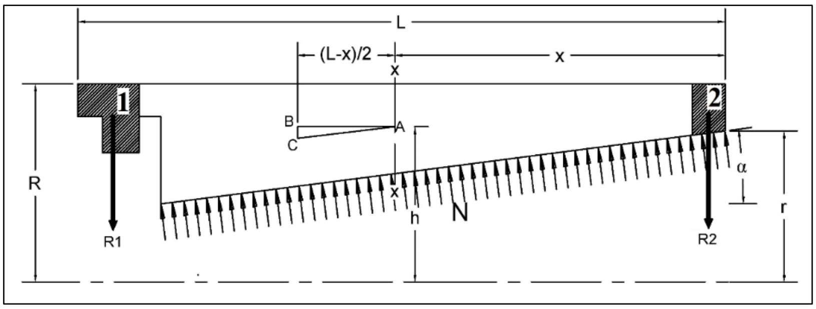
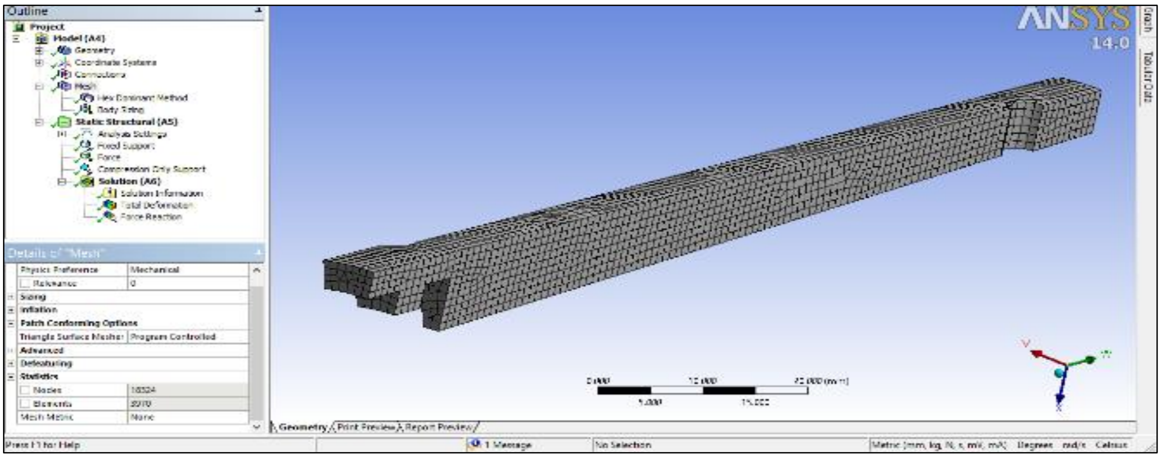


Fig. 16: *Reaction at Supports of a Slit.*

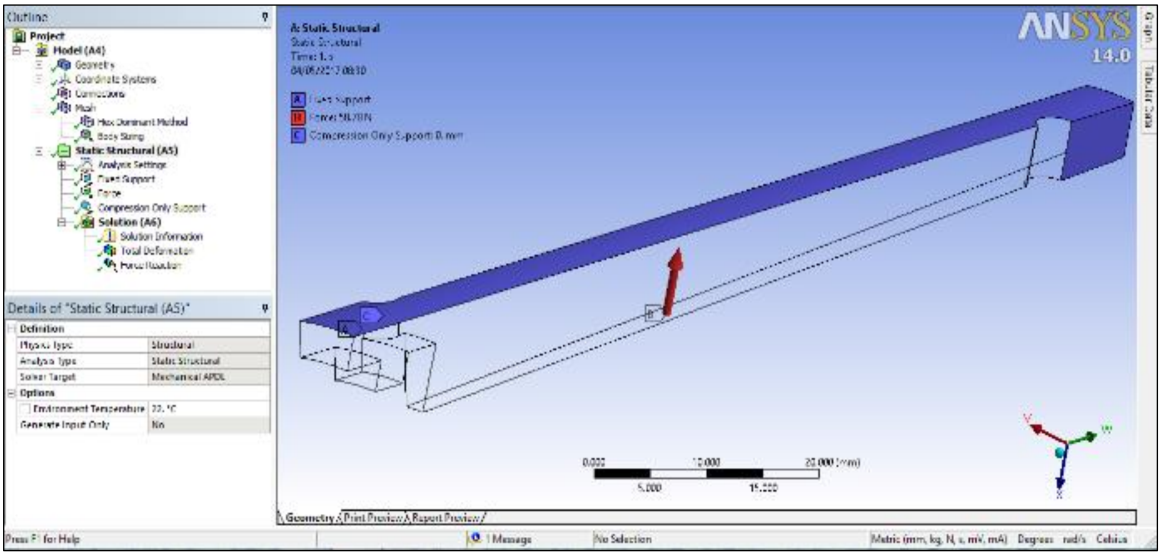


Details of "Mesh"

Physics Preference	Mechanical
☐ Relevance	0
Sizing	
Inflation	
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Advanced	
Defeaturing	
Statistics	
☐ Nodes	16324
☐ Elements	2070
Mesh Metric	None

Metric (mm, kg, N, s, mV, mA) Degrees rad/s Celsius

Fig. 17: *Meshing Condition.*



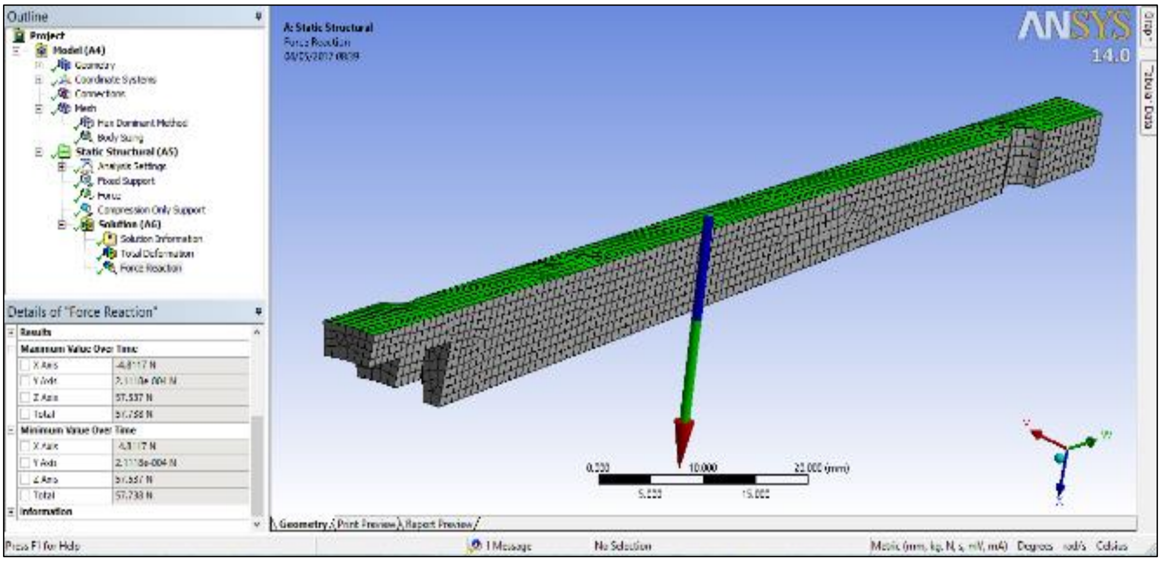
A: Static Structural
Static Structural
Time: 1. s
04/05/2017 08:10

A Fixed Support
B Force: 58.78N
C Compression Only Support: 0. mm

Details of "Static Structural (A5)"

Definition	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	22. °C
Generate Input Only	No

Fig. 18: *Boundary Conditions.*

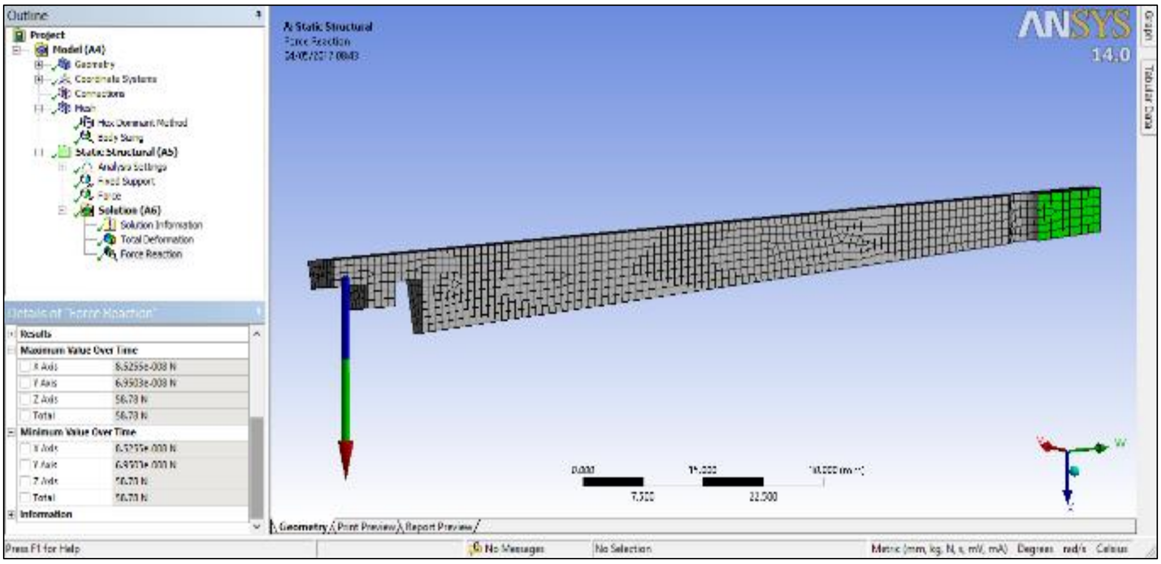


A: Static Structural
Force Reaction
04/05/2017 08:39

Details of "Force Reaction"

Results	
Maximum Value Over Time	
X Axis	-4.8117 N
Y Axis	2.1118e-004 N
Z Axis	57.537 N
Total	57.738 N
Minimum Value Over Time	
X Axis	-4.8117 N
Y Axis	2.1118e-004 N
Z Axis	57.537 N
Total	57.738 N
Information	

Fig. 19: *Result of Reaction of Force at Midspan of Slit of Collet.*



A: Static Structural
Force Reaction
04/05/2017 08:43

Details of "Force Reaction"

Results	
Maximum Value Over Time	
X Axis	6.5255e-008 N
Y Axis	6.9503e-008 N
Z Axis	56.78 N
Total	56.78 N
Minimum Value Over Time	
X Axis	6.5255e-008 N
Y Axis	6.9503e-008 N
Z Axis	56.78 N
Total	56.78 N
Information	

Fig. 20: *Result of Reaction of Force at Supports.*

Table 3: *Comparison of Different Methods of Finding Reaction Force at the Mid-Span of Slit of Collet.*

Sr. No	Method	Reaction of Force at Mid-Span of Beam (N)	Difference (N)	Difference (%)
1	Analytical Approach	58.71	-	-
2	ANSYS Workbench	57.74	0.97	1.65

Table 4: *Comparison of Different Methods of Finding Reaction Force at Supports.*

Sr. No.	Method	Reaction of Force at Supports (N)	Difference (N)	Difference (%)
1	Analytical Approach	29.36	-	-
2	ANSYS Workbench	29.39	0.03	0.10

Here we can see from Figure 19 that force reaction at the centre of slit is 57.74 N, which has same value as of clamping force.
$Ncos(\alpha) = 58.71\,N$
Here, we can see from Figure 20 that the reaction force at the supports is 58.78 N, but as there are two fixed ends,
$R1 = R2 = 58.78/2 = 29.39\,N$

Comparison of Different Method of Finding Reaction of Force

In this section, we have compared results of determining the reaction of force at the mid-span of the beam and at reaction and reaction of force at supports by the analytical method and ANSYS workbench analysis. It concludes that both results are having a greater match.

From Table 3 and Table 4, we can conclude that results through the analytical approach and ANSYS workbench are very similar. So, our method of analytical approach for finding force reaction considering slit of collet as a simply supported beam is valid.

CONCLUSIONS

From this research study following conclusions can be derived:

1. Euler’s beam theory can be successfully applied for finding deflection of the tapered simply supported beam.
2. Using theory of friction, the amount of amplification-clamping force can be found according to the known value of pulling force.
3. The method of finding the reaction of force at the mid-span of the beam is developed, which will be helpful in getting the reaction of force given by clamped workpiece on the collet.
4. The method of designing single angle expanding collets can be useful for finding double angle collets and collapsing collets.
5. The design developed in this research paper can be useful for optimising the taper angle of the collet.

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