e-ISSN:2582-7219

INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH IN SCIENCE, ENGINEERING AND TECHNOLOGY

Volume 7, Issue 4, April 2024

INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 7.521

International Journal Of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

| ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 7.521| Monthly Peer Reviewed & Referred Journal |

| Volume 7, Issue 4, April 2024 |

| DOI:10.15680/IJMRSET.2024.0704187 |

Study of Cumulative Damage of Rigid Flange Coupling and Its Components, and Their Effective Life Prediction under Varying Cyclic Load

Mr. Rahul B Gunale[1], **Om N Malve**[2], **Vishal V Phadatare**[3]

Assistant Professor, Mechanical Department, ICOER, JSPM, Wagholi, Pune, India[1]

U.G. Student, Mechanical Department, ICOER, JSPM, Wagholi, Pune, India[2,3]

ABSTRACT: Mechanical components, especially recommended in the power and motion transfer applications are subjected to effect of repetitive loading and hence adverse effect of stresses induced because of such loadings. Sometime magnitude of such loading acts is constant for one complete cycle of operation and some time it varies frequently within same cycle of operation at frequent. Few of the machine components are experienced by combination of loadings as discussed above. Under such cases designer needs to identify the exact life of components by considering an impact of both such loadings act and hence cumulative component damage occurs.

Component subjected to gradual loading will subjected to normal stress intensity whose magnitude and direction can be predicted with respect to time and thus damage due so such stresses can be easily accommodates while mechanical component design. But stresses induced due to repetitive loading and impact loading is almost double by magnitude and unpredictable in location with respect to time which made process of component design further complicated and tricky one.

The research paper focused on one such aspect, where rigid flange coupling recommended in power and motion transfer application along with its component subjected to versatile stress magnitude and thus involves sudden and instantaneous failure without previous intimation given about. The components are subjected/approaching towards failure with definite work, load and duty performed as a part of complete work cycle, the end result, or component failure is nothing but summation of all such small damages occurred in definite stages one after another till complete and throughout failure of component will not occurs. The component under consideration are combination of ductile and brittle material origin, the strength and life evaluation in terms of SN curve is separate approach derived which tells about what maximum life individual component will spend under condition of loading and operations is maintained.

KEYWORDS: SN Curve, fatigue failure, Cumulative damage, Repetitive loading etc.

I. INTRODUCTION

The rigid flange couplings are popularly known about their higher power transmission capacity and precise operational performance throughout the process with no part assigned for flexibility to move or displaced during. This ensures its highest efficiency in performance and thus highest torque transmission capacity with less space requirement an operation to perform.

The power transmission operation, ensures different nature load acting on coupling components which detailed below,

- Input and output flange of the coupling- Subjected to torsional shear stress and transverse shear stress
- Bolt which holds input and output flange together- Transverse shear stress, torsional shear stress, bending stress (Occasionally, as with respect to time, parts worn out with enlarging hoe diameter within they inserted and thus clearance existed between parts put bolt under bending and occasionally at transverse shear stress. The resultant of maximum shear stress acting will defines part safety or failure if not imparted with required design stability)
- Nut- Subjected to transverse shear stress
- Nut and bolt assembly- Bearing pressure (Impact of which considered negligible under process of power and motion transfer)

The nut and bolt are made of ductile material (Mild Steel, with (s_{yt} = 380 N/$_{mm}$2)), whereas Flanges are made of brittle material (Cast Iron, with (s_{ut} = 180 N/$_{mm}$2)). The analysis of component is not possible to made on same SN curve diagram, thus it has drawn separately for ductile and brittle as well, the average effect of both considered together will defines for what maximum stress or loading cycles component under assembly can performed better without getting failed totally or start malfunctioning.

The approach of research paper defines, journey of design engineer right from component material selection, stress predicting, average damage occurred in component and thus effective work cycles they can withstand for.

II. PROBLEM DEFINITION

Predict the exact life of rigid flange components under the power and motion transfer application as detailed below.

Sr. No.	**Power transmitted (kw)**	**Rpm (Revolution Per Minute)**	**Remarks** (Regarding operation parameter value)
1	50	300	Higher power transmission recommended lower rpm the machine should set on to avoid component damage
2	20	720	Lower power transmission offers flexibility, machine components to operate at higher rpm, the allocated job to get done at earliest possible basis.

The components are mate such a way that, even slight misalignment will causes the error to occur in functioning and slight rise in the level of problem leading entire coupling assembly to fail at instantaneous. Due to fraction of loss in the power due to part misalignment, efficiency of part and thus an assembly can be considered high. The radial/angular space requirement during operation will eliminates totally, thus operational set up can put within compact space let desire work to get done.

For above load acting and operational parameters stated, design coupling and its component with stated definite life time they can perform for satisfactorily without getting fail. (Use the finite life approach and SN curve method in combination to predict the exact life of asked variables/parameters).

III. DISCUSSION OF THE PROBLEM

The rigid coupling as a mechanical assembly widely used in power and motion transfer application requires less radial space as it not tolerates any misalignment among its part during operation. Th efficiency of assembly is high, but slight error will causing major damage not to the assembly components but its operator even. Basically, to require to study the mode of power transfer, during operation.

The input shaft which receives power from motor will transfer to key on the shaft and later to input flange. Th input flange, transfer it to nut and bolt sub-assembly which further transfer it to key on output shaft and thus output shaft to machine component to perform assigned work effectively. Here, set of linkages/junction/part connectivity comes in to picture which in sequence responsible or ensures the power and motion transfer.

Under the effect or way/mode of power transfer, the components are subjected to following loading and hence repetitive stress the magnitude of which tends to vary from cycle to cycle and thus predicting exact magnitude of same goes difficult.

- Input and output shaft: Torsional shear stress and bending stress
- Key’s placed on input and output shaft’s: Transverse shear stress and compressive stress
- Input and output flange of the coupling: Torsional shear stress, Transverse shear stress
- Nut and bolt subassembly: Transverse shear stress/Bending stress, Torsional shear stress

The repetitive loading of unknown magnitude, direction causes component damage in gradual and step by step manner. Every cycle, consumes the component life and pushing it towards the failure. The prediction of component life and thus exact life cycle of component under magnitude of varying intensity stress acting can be predicting by using ‘Cumulative Damage by Using Fatigue Equation’. The approach and methodology for same is discussed in paper. As components are combination ductile and brittle nature, separate effect considered and thus average life calculation which further reduced by considering some untraceable effects and damage occurred because those will quote the exact life of component in terms
‘Million Revolution’ for which component can stand.

IV. FEW OF THE BASIC DESIGN ASPECTS DISCUSSED

FOS consideration: As per fatigue loading is concern, magnitude and direction of stresses are unpredictable, and component deformation under same is negligible. Thus consideration for FOS is given out to be more. Unlike gradual loading, ideal component deformation with showing definite existence for regions like elastic, plastic and failure skipped totally and failure will be instantaneous and immediate irrespective of material nature either ductile or brittle.

Material stress concentration effect:

Ductile material: Effect of notches, groves, holes, cavities, naming impressions liable to induce and enhance effect of material stress concentration, which brought material failure at earliest possible basis. The stress raising effect of such material discontinuities raises magnitude of stress and plastic deformation of component come occur at earliest possible basis, next stage of which failure by neck formation is.
But by the time stress magnitude rises, fiber failure occurs, immediate effect of which stresses redistribution will take place and component will safe longer under assigned impact of stress concentration and loading.

Brittle material: The component failure will sudden and total with no stresses redistribution occurs. Thus rise of stress magnitude, lead component to fail as sudden and total and such an adverse impact of stress concentration in terms earlier material failure can be considered.
Removing material in excess amount, additional drilling for holes, component manufacturing for fillet and radial edges over sharp one are few of the remedial actions can be taken component to protect from adverse stress concentration effects and respective failure going to occur because of same.

Cumulative damage in fatigue and Miners Equation: Component subjected to repetitive impact of loading and thus stresses can be studied, average life of component to predict by using equation called
‘Miners Equation’ and can be expressed as follows,

$$\frac{n1}{N1} + \frac{n2}{N2} + \ldots\ldots\ldots\ldots + \frac{nx}{Nx} = 1$$

Or

$$\frac{\alpha 1N}{N1} + \frac{\alpha 2N}{N2} + \ldots\ldots\ldots\ldots + \frac{\alpha xN}{Nx} = 1$$

Parameter, (α) represents, proportion of component life consumed, by stress intensity (σ) acting for (n) number of cycle. With considering effect of various cycle same or different parameters associated with, added together, the resultant life of component (N) can be predicted by using equation as stated above. The intensity of stress may vary from cycle to cycle, the stress with higher intensity are expected to last over short span of time, where those with lower are expected to last longer to maintain constant functionality of component throughout its work time.
The maximum stress intensity acting throughout work cycle is expected to run low in its magnitude, but unfortunately no such methodology or component design is suggested ever and that is why component is expected to sustain magnitude of all stress intensity acting throughout operation and average of those stresses considered in calculation of resultant component life after. The component life predicted is average number of cycles or minimum number of revolutions or rotations component can perform under intensity of varying magnitude stress acting, before appearing first crack on its surface which further lead component to fail.

V. COMPONENT DESIGN PROCEDURE AND IMPLEMENTATION METHODOLOGY

1. Basic design perquisites considered:

1. Power is ranging between (20 kw to 50 kw), thus average power in design considered is, P_{avg} = (20+50+35)/3 = **35 kw.**
2. rpm (Revolution/Rotation Per Minute) of flange, shaft or motor ranging between (300 to 720 rpm), n_{avg} = (720 + 300+510)/2 = **513.33≅ 514 rpm.**
3. Parameter consideration which become reason to damage mechanical system mainly:

$P = (\frac{2\pi nT}{60*1000})$, as per formulation for power and motion transfer is concern, increased torque responsible in more and more magnitude of torque to be transferred and converse is also true. With rate of power transfer increases, number of rotation also found increase. The increased magnitude of torque requires, lowering the rpm the system to perform in safe zone always.

Because, the uncertainty in parameter impact on system damage based on their role system to perform effectively without undergoing failure, let here consider average impact of both parameters in the analysis further.

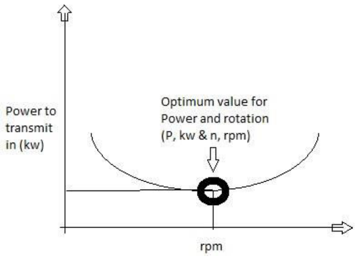
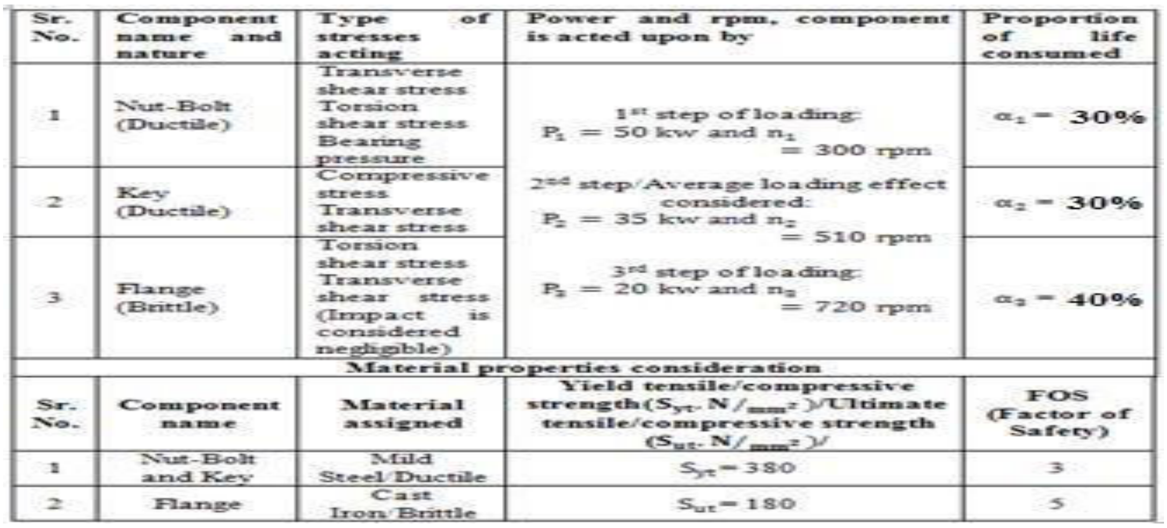


Fig (6.1): Graph to show going for optimum value selection for power and rpm, where average impact and thus component damage is considered.

Tabulation of design data based on hypothesis assumed:



Sr. No.	Component name and nature	Type of stresses acting	Power and rpm, component is acted upon by	Proportion of life consumed
1	Nut-Bolt (Ductile)	Transverse shear stress Torsion shear stress Bearing pressure	1st step of loading: P_1 = 50 kw and n_1 = 300 rpm	α_1 = 30%
2	Key (Ductile)	Compressive stress Transverse shear stress	2nd step/Average loading effect considered: P_2 = 35 kw and n_2 = 510 rpm	α_2 = 30%
3	Flange (Brittle)	Torsion shear stress Transverse shear stress (Impact is considered negligible)	3rd step of loading: P_3 = 20 kw and n_3 = 720 rpm	α_3 = 40%
Material properties consideration				
Sr. No.	Component name	Material assigned	Yield tensile/compressive strength(S_{yt}, N/mm²)/Ultimate tensile/compressive strength (S_{ut}, N/mm²)/	FOS (Factor of Safety)
1	Nut-Bolt and Key	Mild Steel/Ductile	S_{yt} = 380	3
2	Flange	Cast Iron/Brittle	S_{ut} = 180	5

Maximum component damage is considered during 2nd stage of load acting, as power and rpm are acting with maximum possible intensity.

1. Design of nut and bolt sub-assembly: Nut-Bolt sub-assembly receives power from input flange and transfer it to output flange by means of friction (As coupling nature is rigid) the transverse shear strength of nut and bolt as an individual power transmitting element will defines magnitude of maximum power and motion can be transferred to output flange successfully. The stress calculation in nut and bolt is given below,

Bolt design:

Torsion shear stress/Twisting stress/Stress due to twisting moment, $\tau = \frac{16 m_t}{\pi d_c^3}$

Bending stress, $\sigma_b = \frac{M_b Y}{I}$

Maximum shear stress = $\tau_{max} = \sqrt{(\frac{\sigma_b}{2})^2 + (\tau)^2}$

Nut design:

S_b = Bearing pressure = Force per unit area, acting over area enclosed by outer cylindrical surface of bolt and inner cylindrical surface of nut. The maximum value of it, restricted to 10 N/mm^2 (As per specified in design standards)

$S_b = [P/ (\frac{\pi}{4}(d^2 - d_c^2))]$

$\boldsymbol{\tau_n}$ **= (**Transverse shear Load)/(Area under shear failure) = $[P/ (\pi d_c tz)]$

The core diameter of bolt is considered from design table, thus value of pitch (p), nominal diameter (d), mean diameter (d_m), can calculate as per need arise over. Thread thickness is considered half of the pitch.

Resultant stress acting on Nut-Bolt assembly, $(\tau_1) = \tau_{max} + \tau_n$

2. Design of flange assembly: Power received from Nut-Bolt assembly will transferred to output- flange and later to mechanisms through shaft and key assembly. During operation, flange is subjected to Torsional shear stress, which probably involve failure in mechanical component.

$\tau = \frac{16 M_t}{(\pi d_{shaft})^3}$ = Resultant stress acting on flange assembly

3. Design of key: Under the circumstances of power and motion transmission considered, the square key is recommended in to operation. Key element is subjected to compression and transvers shear whose value cane be calculated with the formulation as given below,

$\tau = (2 * M_t)/(d*b*l)$

Where, d- Shaft diameter; b- Width of key; l- Length of key;

M_t-Torque transmitted by shaft.

The compression is hardly could damage the key during operation and so its magnitude is considered as negligible, or it can also be said like, the key is very much safe under compression.

VI. LIFE PREDICTION OF COUPLING COMPONENT'S BY USING FINITE LIFE METHOD

Following loads are considered acting on coupling elements, the magnitude of load is not constant but varies time to time and thus consumes component life in definite amount, thus Miners equation is used to evaluate life cycle of such component for said loading conditions.

- **Nut:** Transverse shear stress.
- **Bolt:** Transverse shear stress.
- **Coupling:** Torsional shear stress.
- **Key:** Transverse shear stress.

Consider the loading conditions for one more time,

Component	**Loading sessions**	**Power (Kw)**	**rpm (n)**
Nut, Bolt, Coupling & Key	1st Part	50	300
	2nd Part	35	510
	3rd Part	20	720
	Average	**35**	**510**

Let we consider an average value of power and rpm acting on component during entire operation to predict their life.

Average value of torque, $P = ((2\pi\ n(M_t)_{avg})/60)$

$\mathbf{(M_t)_{avg} = 962.06\ KN.m = 962063\ KN.mm}$

Tangential force acting on nut, bolt, coupling and key can be calculated by following equation. The shaft diameter is considered as 50mm for said power transmission of 35 Kw throughout the operation.

$(M_t)_{avg} = (F)_{Tangential} * d$
$(F)_{Tangential} = 19.21$ KN
Diameter of bolt: Bolt design is carried out based on maximum shear stress sustaining capacity and so is given as,
$\tau = F_{angential}/(\pi\ dtz)$
Let us consider threads are single start, square threads, having pitch value (5 mm).
Thickness of thread, (t) = Pitch/2 = 5/2 = 2.5mm
Z = Number of threads = Number of starts on threads* Pitch = 1*5 = 5…….(Assuming that thread is singe start square thread)
Maximum shear stress sustaining capacity of thread according to maximum shear stress theory is given as,
$\tau_{permissible} = S_{sy}/FOS = 0.5*S_{yt}/FOS = 0.5*380/3 = 63.33\ N/mm^2$
S_{yt}- Yield strength of material considered as, 380 N/mm^2
FOS- Factor of Safety for ductile & brittle material is considered as, 3.
$d_{Bolt} = 7.74$ mm
Now with considering above diameter, let us find magnitude of shear stress induced in bolt as follows,
$\tau_{Bolt} = T_{angential}/(\pi\ dtz) = 19.24*10^3/(3.14*7.74*2.5*5)$
$\tau_{Bolt} = 63.33\ N/mm^2$
Similarly, let us find out magnitude of shear stress in Nut, key and Coupling.
$\tau_{Nut} = 63.33\ N/mm^2$
τ Coupling = 115 N/mm2
$\tau_{Key} = 88.47\ N/mm^2$
Summarization the values of shear stresses in to the components of coupling assembly,

Sr. No.	**Component**	**Stress value, τ** (N/mm^2)
1	Bolt	**63.33**
2	Nut	**63.33**
3	Key	**88.47**
4	Coupling flange	**115**

VII. ULTIMATE AND YIELD STRENGTH PREDICTION OF COMPONENTS BASED ON MAXIMUM STRESS SUSTAINING CAPACITY

The relation between material shear stress, yield strength and ultimate strength can be expressed as follows,
$\tau = 0.30\ S_{yt}$
$\tau = 0.18\ S_{ut}$
Using above formulation, value of ultimate shear strength of coupling components obtained can be summarized in the table below,

Component	**Ultimate shear strength, S_{ut}, (N/mm^2)**
Bolt	380
Nut	380
Key	380
Flange Coupling	200

VIII. ENDURANCE STRENGTH CALCULATION FOR THE COMPONENTS

$S_e = K_a * K_b * K_c * K_d * S_e'$
In above equation,
S_e'- Laboratory strength of specimen, N/mm^2
K_a- Surface finish factor, and considered as **(1)**
K_b- Size factor, and considered as **(0.75)**
K_c- Reliability factor, and considered as **(0.897)**
K_d- Modifying factor, and calculated as follows,

$$K_d = \frac{1}{K_f} = \frac{1}{1+(q*(K_t-1))} = \frac{1}{1+(0.86\ (1.8-1))} = 0.5924$$

Where,

K_f - Fatigue stress concentration factor

K_t - Theoretical stress concentration factor q- Notch sensitivity factor

So the endurance strength for the bolt is,

$(S_e)_{Bolt}$ **= 60.57 N/mm²**

Similarly the endurance strengths for other elements can be calculated, the values are summarized in the table below,

Component	**Endurance strength, S_e (N/mm²)**
Bolt	**60.57**
Nut	**60.57**
Key	**60.57**
Flange Coupling	**31.88**

Now Life prediction of coupling component by Finite Life Method is processed as follows,

Bolt Life Prediction			
Parameter	**Log Equation**	**Log value**	**Final answer**
0.9 Sut	$\log_{10}(0.9\ S_{ut})$	Log10 (0.9*380)	2.534
Se	Log10 (Se)	$\log_{10}(60.57)$	1.78
τ 1	Log10 (τ 1)	$\log_{10}(63.33)$	1.80

Depiction of values from above table in to SN Curve,

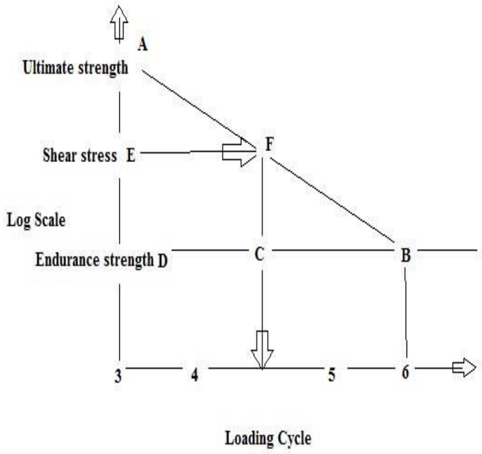


Fig (9.1): S-N Curve, depicting values of Material endurance strength, Ultimate strength, induced shear stress verses corresponding life of the component with respect to each such strengths.

From above graph, value of EF can be calculated as,

EF = DB______ADAE = (6-3)*(log100.9Sut- log10τ)/((log100.9Sut- log10Se))

EF = (6-3)*(log100.9∗380- log1063.33)/((log100.9∗380- log1060.57)) = 2.36

Total life cycles component can sustain, $\log_{10}^{N}$ = 3 + EF = 3 + 2.36 = 5.36

N $_{nut}$ **= 831763 Cycles**

N $_{bolt}$ **= 831763 Cycles**

N $_{key}$ **= 229086 Cycles**

N $_{coupling}$ **= 23384 Cycles**

Nut Life Prediction

Parameter	**Log Equation**	**Log value**	**Final answer**
0.9 Sut	$\mathrm{Log}_{10}(0.9\ S_{ut})$	Log10	2.534
		(0.9*380)	
Se	Log10 (Se)	Log10 (60.57)	1.78
τ 1	Log10 (τ 1)	Log10 (63.33)	1.80

Key Life Prediction

Parameter	**Log Equation**	**Log value**	**Final answer**
0.9 Sut	$\mathrm{Log}_{10}(0.9\ S_{ut})$	Log10 (0.9*380)	2.534
Se	Log10 (Se)	Log10 (60.57)	1.78
τ 1	Log10 (τ 1)	Log10 (88.47)	1.946

Flange Coupling Life Prediction

Parameter	**Log Equation**	**Log value**	**Final answer**
0.9 Sut	$\mathrm{Log}_{10}(0.9\ S_{ut})$	Log10 (0.9*200)	2.25
Se	Log10 (Se)	Log10 (31.88)	1.50
τ 1	Log10 (τ 1)	$\mathrm{Log}_{10}(115)$	2.06

Use of Miners equation to find effective life of coupling assembly under said loading conditions is described as follows,

The equation has implemented considering certain assumptions which are as follows,

1. Let us consider rigid flange is assembly with flange, key, shaft, nut and bolts are its components.
2. The every component is acted upon by certain stress magnitude and such stresses not only consume the life of component but of assembly too. So percentage of component life consumed is considered as life of assembly consumed itself.
3. Nut and bolt are acted upon by same magnitude of shear stress which further leads their failure, i.e. 63.33 N/mm^2. Let us consider nut and bolt with acted upon by said magnitude of stress consumes 15% each the total life of coupling.
4. The key is next element in assembly which is acted upon by stress magnitude of 88 N/mm^2 and consumes 30% life of the assembly.
5. Flange is acted upon by highest magnitude of stress and thus contributes maximum percentage of assembly life consumes, i.e. 40%

The Miners equation with all above hypothesis can be implemented to find resultant life of rigid coupling for said loading, as follows,

0.15 0.15 0.4 0.3 1 ____+ + ________ ____ _+ =

$N_{but} N_{bolt}{}^{N}{}_{coupling} N_{key}\quad N$

(0.15/831763) + (0.15/831763) + (0.4/23384) + (0.3/229086) = 1/N

N = Resultant life of rigid coupling under said loading conditions and specifications = **53304.90 Cycles**

IX. OVERALL RESULT SUMMARY

The table below summarizes the effect of loading which tends to vary after equal or unequal interval of time, thus stresses induced, and life of components consumed in different proportions by such stresses developed. The same results used in the calculation of resultant life of component under mentioned loading conditions.

Component	**Loading sessions**	**Power (Kw) & rpm (N)**	**Endurance Strength, (N/mm^2)**	**Shear stress, (N/mm^2)**	**Life of component consumed (α)**	**Component life in cycles, (N)**
Bolt	1st Part	50, 300	**60.57**	**63.33**	15%	831763
Nut	2nd Part	35, 510	**60.57**	**63.33**	15%	831763
Key	3rd Part	20, 720	**60.57**	**88.47**	30%	229086
Flange Coupling			**31.88**	**115**	40%	23384

Table (10.1): Table shows loading vs resultant life of component.

The resultant life of Rigid Flange Coupling for said loading conditions, said consumption of life happed under the action of stresses is, **N= 53304.90 Cycles**

The alternative use of material, working methodology, would tend to enhance material strength and thus life of coupling too.

X. CONCLUSION OF THE STUDY

The cumulative damage of Rigid Flange Coupling in fatigue loading leads to withdraw following conclusions,

Material endurance strength is less than ultimate strength, and that reveals failure during fluctuating load is sudden and surprise unlike the one occurred during statics load.

Material is not deformed to full capacity of its plastic deformation but fails much prior of yield limit and that requires to consider high factor of safety in component design, in few of the cases, wrong decision taken about factor of safety value, either component would be deigned over safe or not safe and leads to fail quite below than before completion of its expected number of work cycles.

The effect of stress concentration which comes arrived due to irregularities and discontinuities in material geometry; is more severe in fatigue lading than static loading.

The brittle materials need to design considering more value for FOS than ductile, as ductile gives intimation about failure but failure in brittle material would be quite different, and can be considered as sudden and total.

The laboratory endurance strength of specimen is higher than actual strength, as laboratory strength do not considers the effect of parameters such as surface finishing, size factor, notch sensitivity factor etc. which brings the component strength down.

The Fluctuating load is set of varying forces acting on component during its operation tenure which causes component failure surprisingly. The capacity of deformation of component is also not utilized to the extent it could be and failure occurs before yield limit of component material. The endurance strength of component is less than static yield or ultimate strength of component.

Fluctuating load exhibits the pattern of varying load or stress during work tenure of component, and stresses of such varying magnitude tends to consume the component life by equal or unequal proportion with respect to time. The highest load sustaining capacity of component for entire working time, or time before first failure crack appears on material surface is called as, material fatigue strength.

Maximum value of stress, acting for long span of time consumes component life by greater margin.

The stresses acting on nut and bolt are minimum in magnitude and thus they consumes only 15% life of entire coupling assembly, where stresses acting on flange are maximum in magnitude and thus consumes 40% life of assembly, next to flange, key which is acted upon by stress value of 88 MPa consumes 30% life of the component.

The resultant life of coupling assembly is the result of varying magnitude of stresses acting on its component in said range, for said time with definite proportion of life keeps consumed.

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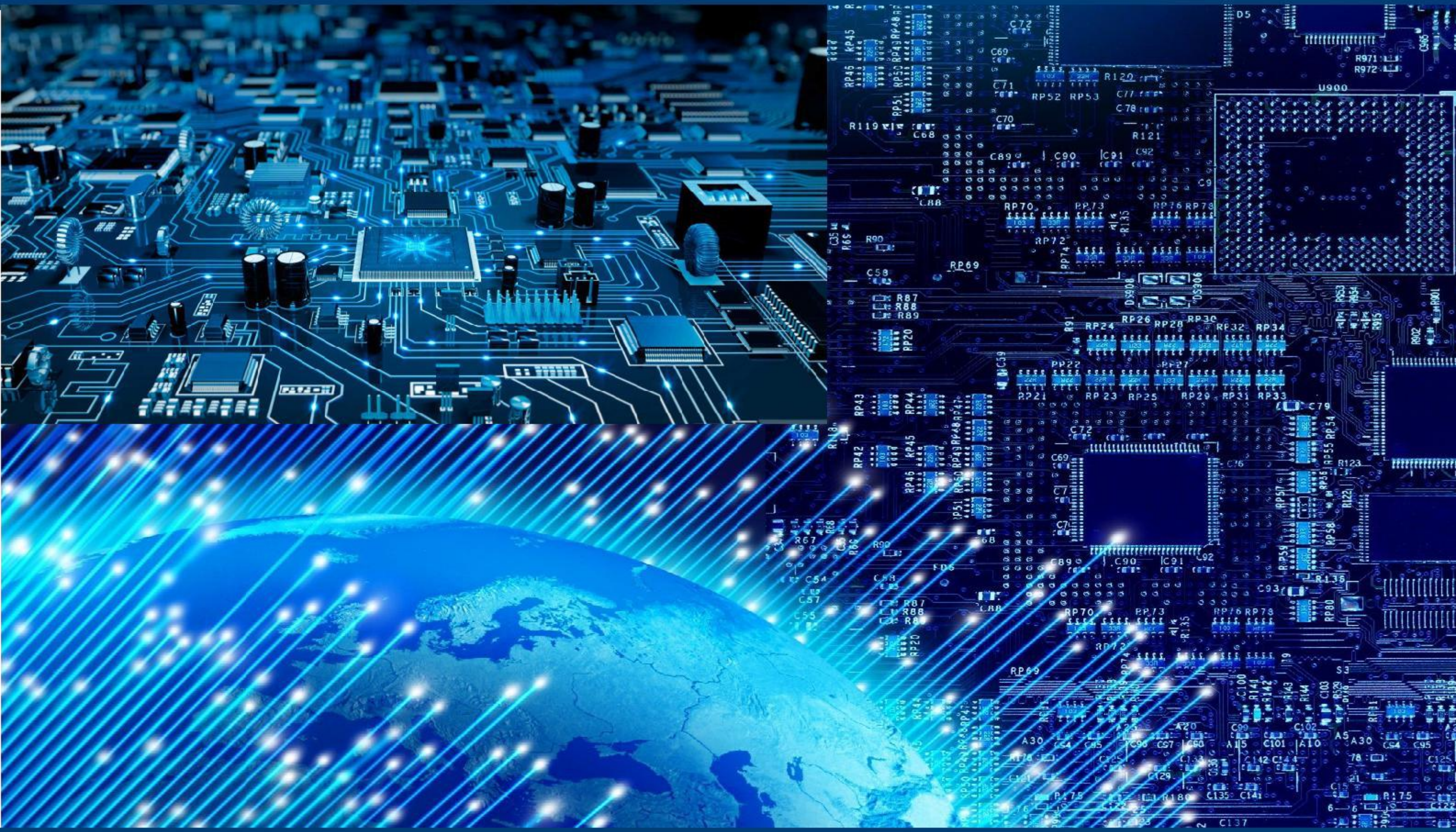

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