Optimization of the Keyway Design with Consideration of Effect of Stress Concentration on Different Materials

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***Abstract* - Key and keyways are one of the most important techniques used for the coupling purpose. These are commonly used in shaft-hub connections. Despite knowing the importance of this a very little research work has been reported in this field. The failure of key and keyways occurred due to the stress concentration in certain areas of machine element. This paper reports the location of stress concentration and compare the results obtain by theoretical analysis with the analysis done by analysis software (Ansys11.0) for different shapes of key and keyways on different materials. The main reason of failure of shaft and keyways in shaft-hub connection is the shear stress, so the focus is done on it. Using shape optimization by providing chamfer and fillet at corners, it is shown that the fatigue life of keyways can be greatly improved as comparison to simple rectangular and square key. On the basis of analysis we conclude that the shaft made by stainless steel having keyway with circular fillet will undergo minimum magnitude of the maximum shear stress in comparison to other material and shapes used for analysis.**

Keywords: *Keyways, Shaft, Stress concentration, Shear stress, Torque, Fillet, Chamfer, Analysis, Photoelastic method.*

INTRODUCTION

Keys and keyways commonly perform connection of shaft and hubs. The major function of a key is to transmit the torque from the shaft to the hub of the matting element and vice versa and is also used to prevent the relative motion between the shaft & the joint element like gear or pulley. To accommodate the key into the shaft a slot is cut into the shaft which is known as the keyway. In the field of design N L Pedersen [1] work on effect of stress concentration and optimization of keyway design using numerical finite element analysis for the prediction of stress concentration in the keyway. The key and keyway design is fully controlled by the standards based on only one parameter – the shaft diameter. It is remarkable that very little effort has been made to improve the design with respect to fatigue, i.e. by minimizing the stress concentrations. In this field Orthwein [2] and N L Pedersen [1] has reported some useful literatures, except them there is Merritt et al. [3] and Kuske et al. [4] who provides different shapes of key. The paper addressing the torsional stiffness of shafts with a kind of keyway is probably that of Filon [5]. In this paper, the shafts were modeled with elliptical cross-section and the keyways were modeled as hyperbolae. Based on this work many experimental analyses have been carried out using Photoelastic analysis [5], [6], [7], [8], [9] and [10]. Some used electroplating technique for prediction of stress concentration [11] and [12]. By W. C. Orthwein [13] a review of the history of the analysis of torsionally induced shaft stresses due to the inclusion of an empty keyway, or key seat, is given with emphasis placed upon experimentally measured values. According to H Fessler, CC Rogers & P Stanley [14] the frozen-stress photo elastic technique has been used to determine the complete surface stress field in empty keyways of British Standard proportions for rectangular keys. A method is included for the photo elastic analysis of general surface stresses in doubly curved surfaces with one small radius.The experimental technique consists of Elastomer Models, Brittle Coating and Photoelastic Technique. In this work shafts were modeled with circular cross section and are having two different shapes of the keyways .One keyway is modeled as having rectangular cross section with circular fillet & the other keyway is provided with chamfer .The use of FE modelling and computational power makes it possible to improve the design of the keyway but it seems that this has not yet been done. The purpose of the present work is therefore to improve/optimize the keyway design by comparing the results obtained by the stress analysis of shaft with three different materials & two different shapes of the keyway.

A number of variations occur during the experiment /analysis of the shaft. This are-

a. Type of Loads applied: tension, bending or torsion.

b. Position of the Keyi.e. loaded with or without the key inserted in the keyway.

c. Stresses are generated at the keyway part and the shaft.

Restricting the numerical analysis the present work deals only with torsion, with respect to the other loads or any load combinations. To make easy comparison to the

numerical and experimental values, the keyway is loaded in torsion without the key.
For these work, tools used is the CAD software Pro Engineer Wildfire 4.0 for generating the part model of the shaft & the CAE software ANSYS 2011 for the analysis of the stresses developed in the shaft.

NOMANCLATURE

b	width of keyway
C	Constant
d	diameter of shaft
e^x	ten to the power x
G	shear modulus
H	angular rotation per length
J	torsional stiffness factor of cross-section
K_t	theoretical stress concentration factor (normal stress)
K_{ts}	theoretical stress concentration factor (shear stress)
Kg	Kilogram
l	length of shaft
M_t	torsional moment
m	Meter
n	normal vector component
N	Newton
r	fillet radius
s	Second
t	depth of keyway

GREEK SYMBOL

τ_{max}	maximum shear stress
τ_{nom}	nominal shear stress
σ	normal stress
σ_{max}	maximum stress
σ_{nom}	nominal stress
τ	Shear Stress
°C	Degree Centigrade

ACRONYMS

FEM	Finite Element Methods
FEA	Finite Element Analysis
MPa	Mega Pascal

STRESS CONCENTRATION

In developing a machine it is impossible to avoid changes in cross-section, holes, notches, shoulders etc. Some examples are shown in figure below;

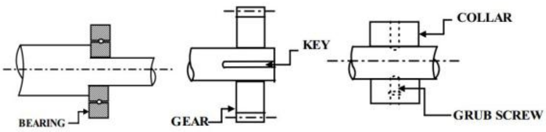

Fig - some typical illustrations leading to stress concentration

Any such discontinuity in a member affects the stress distribution in the neighbourhood and the discontinuity acts as a stress raiser. It is possible to predict the stress concentration factors for certain geometric shapes using theory of elasticity approach.
Stress concentration factors may also be obtained using any one of the following experimental techniques:

1. Strain gage method
2. Photoelasticity method
3. Brittle coating technique
4. Grid method

The stress concentration in keyways when torque is transmitted through key is a difference in the maximum stress for pure torsional loading without the key relative to torsion applied through the key. These values were rather unaffected by different ratios of fillet radius to shaft diameter. This leads to the conclusion that the true stress concentrations can be found from a study without the torsion coming from the key by adding at maximum 12% to the stresses in the prismatic part. Circular design, this would most probably increase the machining cost and is not discussed further in this paper.
For more accurate estimation numerical methods like Finite element analysis may be employed.
Theoretical stress concentration factors for different configurations are available in handbooks. Some typical plots of theoretical stress concentration factors and r/d ratio for a stepped shaft are shown in figure below;

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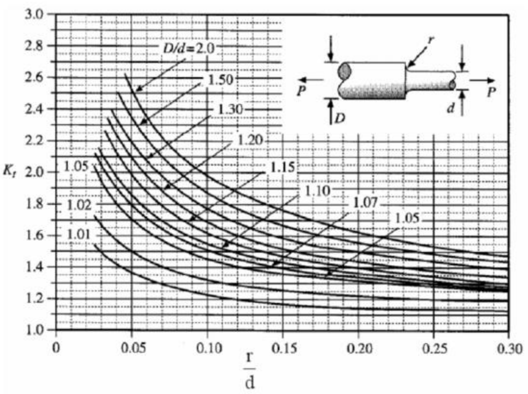


Fig - Variation of theoretical stress concentration factor with r/d of a stepped shaft for different values of D/d subjected to uni-axial loading.

MATHEMATICAL MODELING

In design under fatigue loading, stress concentration factor is used in modifying the values of endurance limit while in design under static loading it simply acts as stress modifier. This means

Actual stress= k_t ×calculated stress

For ductile materials under static loading effect of stress concentration is not very serious but for brittle materials even for static loading it is important. It is found that some materials are not very sensitive to the existence of notches or discontinuity. In such cases it is not necessary to use the full value of k_t and instead a reduced value is needed. This is given by a factor known as fatigue strength reduction factor k_f and this is defined as

$$k_f = \frac{\text{Endurance limit of notch free specimens}}{\text{Endurance limit of notched specimens}}$$

Another term called Notch sensitivity factor, q is often used in design and this is defined as

$$q = \frac{k_f - 1}{k_t - 1}$$

The value of 'q' usually lies between 0 and 1. If q=0, $k_f = 1$ and this indicates no notch sensitivity. If however q=1, then $k_f = k_t$ and this indicates full notch sensitivity. Design charts for 'q' can be found in design hand-books and knowing k_f, k_t may be obtained.

DESIGN PROBLEM

The major problem associated with the keyway of the shaft is stress concentration, which is the localization of the higher magnitude stresses at the place where abrupt change in the cross section takes place. This stress concentration affects the stresses induced into the shaft & becomes the critical factor while designing a shaft.

MODELING AND ANALYSIS

Simple parameterization and due to previous results obtained with this shape in relation to stress concentrations for other problems. From a practical point of view focus should be on simplicity, although the optimization result should still benear to the optimal design. That a given parameterization is sufficiently flexible, i.e. that it can return optimal designs, can only be checked or verified after an actual optimization procedure. If the stress is constant along major parts of the surface then the shape is assumed optimal.

In keyway design as in many other designs within machine element the standard preferred shape is the circle or a semicircle. This is probably due to the simple parameterization and/or ease of manufacturing. For the sled-runner design or the profile keyway there are however no difficulty in introducing a different shape. It is well known from shape optimization that the circular shape of fillet is seldom optimal with respect to stress concentrations.

The methodology used in this project is to provide chamfer instead of a circular fillet to the keyway of the shaft made of different-different materials.

DESCRIPTION–

ModelGeometry

A muff coupling has to connect to different material shaft transmitting 25KW power at 360 rpm. The Shaft Diameter (d) is 45 mm, sleeve Diameter (D is 105 mm, Length of sleeve (L) = 160 mm and the Length of the key is 80 mm. where, the Standard Dimension for key = 14mm x 9 mm.

Material Assignment

Many industries manufacture the Key by plain carbon steel. In this paper, we perform the stress analysis of keyways which is manufactured by the 3 different materials and of 2 different shapes. The different materials we used in this analysis are Grey Cast Iron, Structural steel and Stainless steel. The different shapes are with chamfer and without chamfer. The complete design optimization is performed in the ANSYS 11.0 software.

Stress analysis of key by ANSYS Software

The keys are subjected to a load of 29743 N (ramped). The different types of material used with their properties are:

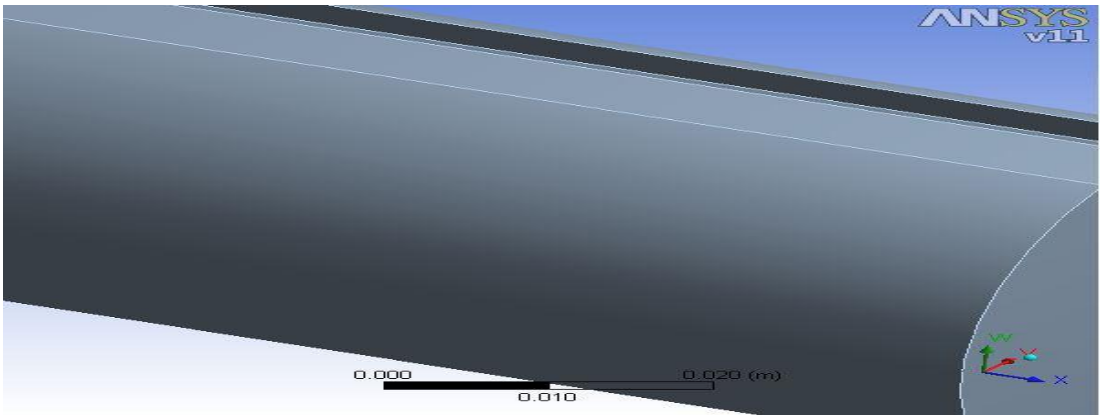
Material Properties of Design materials:

Grey Cast Iron	
Young's Modulus	1.1e+011 Pa
Poisson's Ratio	0.28
Density	7200. kg/m³
Thermal Expansion	1.1e-005 1/°C
Tensile Yield Strength	0. Pa
Compressive Yield Strength	0. Pa
Tensile Ultimate Strength	2.4e+008 Pa
Compressive Ultimate Strength	8.2e+008 Pa

Structural Steel	
Young's Modulus	2.e+011 Pa
Poisson's Ratio	0.3
Density	7850. kg/m³
Thermal Expansion	1.2e-005 1/°C
Tensile Yield Strength	2.5e+008 Pa
Compressive Yield Strength	2.5e+008 Pa
Tensile Ultimate Strength	4.6e+008 Pa
Compressive Ultimate Strength	0 Pa

Stainless Steel	
Young's Modulus	1.93e+011 Pa
Poisson's Ratio	0.31
Density	7750. kg/m³
Thermal Expansion	1.7e-005 1/°C
Tensile Yield Strength	2.07e+008 Pa
Compressive Yield Strength	2.07e+008 Pa
Tensile Ultimate Strength	5.86e+008 Pa

RESULT AND DISCUSSION



ANSYS PROCEDURE FOR Static Structural

ANALYSIS

- Model
  1. Geometry- Imported from PROE in ".iges" format. Geometry imported in ANSYS is Solid.
- Mesh- triangular element selection.
- Static Structural

  1. Analysis Settings- it is being used for static structural, single step loading.
  2. Loads- The model is working under the load of 29743 N.
  3. Solution- Equivalent (Von-Mises) Stresses

Based on the analysis done, we get the result which is tabulated below as follows:

SI .No.	Material	Nodes		Von-Mises (With chamfer), (MPa)	Von-Mises (with circular fillet), (MPa)
		With chamfer	With circular fillet		
1	Grey Cast Iron	9065	8887	100.88	94.07
2	Structural steel	9065	8887	94.95	92.45
3	Stainless steel	9065	8887	93.87	91.44

DISCUSSION:

Above table shows that the value we get of Von-Mises stresses varies with the different design of the keyway manufactured with the different materials. For grey cast iron material key with chamfer shape, the stresses developed are around 100.88 MPa, whereas with circular fillet it is near about 94.07 MPa. Similarly for structural steel key with circular fillet shape stress reduces to 92.45 MPa as compared with the stress developed in chamfer shape i.e. 94.95 MPa. But the optimized result that we obtained through analysis is by using the Stainless Steel with circular fillet shape. The value of stress developed is 91.44 MPa which is minimum value of Von –Mises stress as compared to different materials with different shapes used for analysis.

CONCLUSION:

On the basis of above data we can conclude that the shaft made by stainless steel having keyway with circular fillet will undergo minimum magnitude of the maximum shear stress rather than other mentioned options & for this particular case our design will get minimized. The numerical results obtained from the software are in good agreement with those from experiments. The numerical simulation confirms that ANSYS should be a suitable tool for predicting the stress concentration and optimizing the design of the keyway. The results presented in this paper are of great significance on the optimum design of keyways.

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