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DESIGN OF THIN CURVED SENSOR TO MEASURE CONTACT SLIP IN FRETTING EXPERIMENTS

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Abstract:

This paper proposes a new thin curved sensor/strip to measure the relative slip between pad and specimen under fretting conditions. Since the relative contact displacement is a vital parameter to categorize the fretting process, the measurement of contact displacement between pad and specimen is necessary. The spring steel has chosen to fabricate the thin curved strip because of its high yield strength and the ability to return to its initial position even with notable deflection. Before the fabrication, Finite Element Analysis (FEA) was performed on the thin curved sensor. The strip consists of different shapes (rectangular, circular, and elliptical) of slots, and the number of slots in each strip is varied from 2 to 6. The Strain Energy Approach (SEA) has been used to calculate the displacement for the curved strip, and it was compared, verified, and validated with its FEA and Experimental results. Four configurations were chosen from FEA study of thin curved strips with slots to measure micro-level displacement between pad and specimen under fretting experiments. The present study reveals that the increasing number and size of holes in the curved strip increases displacement and von-Mises stress values, which ensure higher flexibility to the strip. The reduction in the area and minimum thickness of the curved strip could be the reason for the decrease in the stiffness of the curved strip. This study explores using a new novel and straightforward instrument/sensor to capture the micro-level relative displacement between the pad and specimen under fretting conditions.

Keywords: Finite element analysis, fretting, thin curved strip, contact displacement, relative slip.

1. Introduction

Fretting is a failure phenomenon which occurs between two mechanically fastened/clamped parts, when these parts subjected to a micro-level relative slip between contact interfaces due to external cyclic forces and moments. In fretting, the displacement amplitude ranges from 0 to 300 µm (Waterhouse, 1984). The sliding usually occurs tangentially between the contacting surfaces subjected to fretting. There are two important fretting modes commonly observed in machine components (Vingsbo, O. and Söderberg, S., 1988); Partial slip fretting and Gross slip fretting. Partial slip fretting comprises two regimes, namely "Stick regime" wherein the points is not having any relative movement and "Slip regime" wherein the points in the contact interfaces undergoes relative sliding (Neu, 2011). In a complete cycle, a condition at which all the points in the contact interfaces of contacting bodies experience relative slip is known as gross slip. Illustration of the above two stages of fretting is depicted in Fig. 1. Fretting causes damage between contact interfaces in two ways: either by shortening the fatigue life of the parts (fretting fatigue) or by deteriorating surface of contact interfaces (fretting wear). Both the damages result in premature failure of the parts. Fretting failure is observed usually in machine components such as bolt and nut arrangements, riveted joints, interference fits, turbine blade dovetail joints, key-way shaft and spline couplings, marine risers, and pipe fittings which are experiencing cyclic loads while transmitting machine loads or due to the vibration of the machine (Sunde et al., 2018). Raja pandi et.al (2019) investigated the one-dimensional FEA and design of different rig structure by considering the changes in the length of the horizontal beam and vertical support, eleven cases of design in the fretting rig were formed and its analysis are performed with suitable boundary conditions by using ANSYS software.

The fretting fatigue process causes more damage than the fretting wear process to the machine components. Fretting fatigue is the predominant damage occurring in partial slip fretting tests. The small tangential amplitude, high friction coefficient occurring between contact interfaces induces high tractional forces and high

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bulk stress to create premature fatigue failure with crack initiation followed by crack propagation. Since the sliding is not persisted in the stick regime of partial slip tests, fretting wear is more associated with gross slip fretting tests (Pasanen et al., 2009).

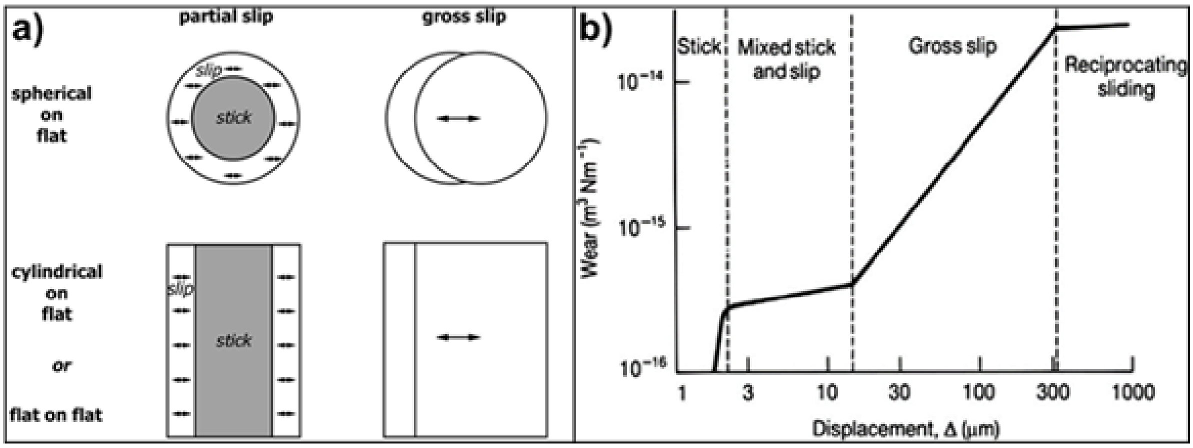

Fig. 1: (a) Illustration of stages in the fretting process by considering slip movement (Neu, 2011); (b) Illustration of the dependence of wear coefficient with displacement amplitude in fretting concerning the slip regime (Vingsbo and Söderberg, 1988)

Collins (1965) has introduced the damage factor concept for the fretting fatigue process and grouped the parameters into eight categories. More than 50 parameters which are influencing the fretting process have been identified (Dobromirski, 1992). Among these parameters, the primary parameters which affect the fretting are coefficient of friction, normal force, shear traction, and slip amplitude. Tangential slip under the contact interface has been affected by the normal force, tractional force, and coefficient of friction, though all are interdependent (Hills, 1994). Various studies have shown the use of slip amplitude length as an identification parameter to describe the partial slip and gross slip changes during the fretting process. An increase in slip amplitude length has been considered to increase the fretting wear damage (Fig 1:b). However, slip amplitude also has a strong influence on fretting fatigue damage (Vingsbo and Söderberg 1988 & Fouvry et al. 1996). In fretting fatigue, the crack initiation and crack propagation time are affected by various factors (contact stresses, frequency, environmental conditions, etc.), including slip amplitude.

Measurement of relative slip between pad and specimen is necessary for completing the functional requirement to identify the changes of fretting regimes. Slip amplitude measurement at the contact interface under fretting is a tedious and an important job to characterize the fretting process. In fretting, measurement of slip amplitude has been done either by using devices such as Eddy current non-contact transducers (Farrahi and Maeder, 1992), extensometers (Lee et al, 2007), Linear Variable Differential Transformers (LVDTs) (Walvekar et al., 2014), laser displacement sensor (Ferrero et al., 2004) and Capacitance position sensor (Favrow et al., 2000 & Vadivuchezhian et al., 2011) or by adopting Digital Image Correlation (DIC) (Juoksukangas et al., 2017) method. The above-mentioned slip amplitude measuring techniques/method, except DIC, usage of devices involve difficulties which are as follows; usually slip amplitude is in micron level or even less than micron level and it is hard to measure at the contact interface by adopting the above-mentioned devices, the possibility of error occurrence in the slip measurement due to the inclusion of compliance effect of measuring device and test device and difficulties involved in installation of measuring device at the contact interface (Ramalho and Celis, 2003 & De Pauw et al., 2014). So, there is a need for the development of simple and precise apparatus to measure contact slip and make an apparatus into widely usable one.

This paper proposes a new strip and sensor arrangement to estimate the relative slip between pad and specimen under fretting conditions. To accomplish this, a numerical and analytical study of the proposed thin curved strip with the strain gauge, usually termed here as "sensor," was performed. The validation of displacement value obtained from both analytical and numerical approaches has been done by conducting experiments with a thin curved sensor.

2. Methods and Materials

The present study involves the design of thin-walled curved sensor to measure the relative displacement between the pad and the specimen during fretting experiments. As stated earlier, usually the relative displacement is in micron or even less in scale, hence the displacement sensor should merely stretchable when the load is applied and also be able to retract back to its original position when the applied load is removed. Thin flat strip hasn't been considered due to the applied load on the specimen would be acting in the lateral direction of the strip. So, thin curved strip has been selected, with and without slots on it, for the analysis. The design process of thin curved sensor was done by adopting the following two approaches; Strain Energy Approach (SEA) and Finite Element Analysis (FEA).

2.1 Strain energy approach (SEA)

As part of the preliminary design process, a thin curved strip without slot has to be modelled, and it is used for finite element study. The thin curved strip without slot is shown in Fig. 2: a. Before doing the finite element analysis, the Strain Energy (SE) approach was used to find the maximum deflection, the deflection at the middle of the strip and maximum stress of the thin curved strip and the formulae have been given in Eq. (1), (2) and (3). The formulae have been derived from strain energy approach and pure bending equation.
For the thin curved strip,

Maximum deflection along loading direction,

$$\delta_{\max} = \left(\frac{3\pi}{2}\right)\left(\frac{P*r^3}{E*I}\right) \tag{1}$$

Deflection at middle along loading direction,

$$\delta_{mid} = \left(\frac{\pi}{2}\right)\left(\frac{P*r^3}{E*I}\right) \tag{2}$$

Maximum Bending Stress,

$$\sigma_{\max} = \left(\frac{M*y}{(r_n - y)*A*e}\right) \tag{3}$$

Where P is applied normal load in N, r is the mean radius of the thin curved strip in mm, E is elastic modulus of the strip material in N/mm^2, I is moment of inertia of strip in mm^4 and M is maximum moment acting on the strip in N.mm. For the curved sections, the neutral layer axis is not coinciding with the centroidal axis of the section (S. Timoshenko, 1955). So, the distance between the neutral axis and the outer layer is referred as y in mm (Fig 2: b). Since, the consideration of the rectangular curved section for the thin strip, the radius of the neutral axis (rn) is calculated by the following Eq. (4).
Radius of neutral axis,

$$r_n = \left(\frac{A}{\int\left({dA}/{r}\right)}\right) = \left(\frac{b*h}{b*\ln\left({r_o}/{r_i}\right)}\right) \tag{4}$$

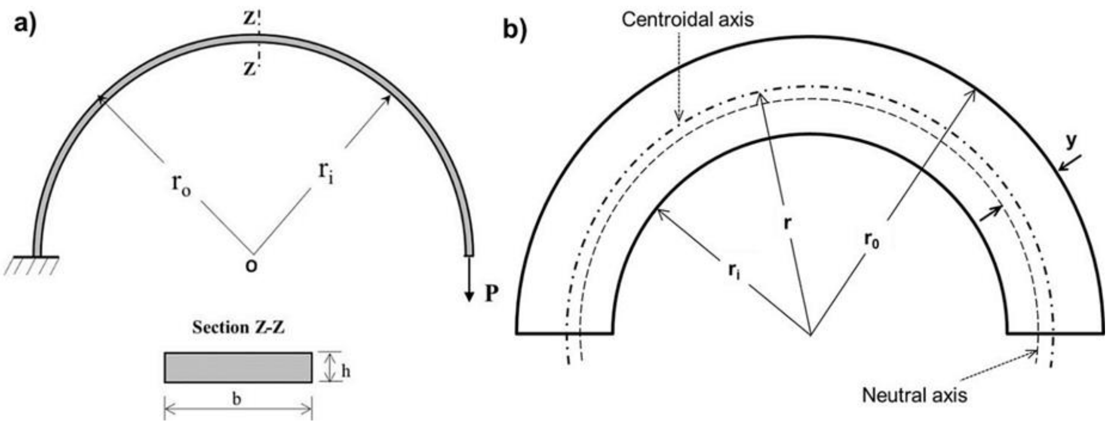

Fig. 2: a) Thin curved sensor without slot; b) Schematic view of curved beam with neutral axis shift from centroidal axis (magnified view)

2.2 Finite element analysis (FEA)

The FEA has been performed using ANSYS with SOLID185 element for the solid model and SHELL181 element for the surface model. SOLID185 element has eight nodes and each node has three translational degrees of freedom (u, v and w). SHELL181 is a four-node element and it has six degrees of freedom at each node (three translations (u, v and w) along three axes (X, Y and Z) and three rotations (θx, θy and θz) about the three axes).

The thin slotted strip can capture least possible displacement values and possess lower stiffness value and higher flexibility than the strip without slot for the same applied load. So, the thin slotted curved strip has been considered as a simplified suitable arrangement to measure small displacement at the contact interface under fretting condition.

Finite element analysis of thin curved strip with different slots have been done with various dimensional modifications involved in the thin strip with different slot type, slot size, number of slots, fillet radius of slot and the width of thin strip and their details are as follows:

The thin strip with rectangular slots, circular slots and elliptical slots were considered for Finite Element study. The number of slots and their dimensions is different for each case and the number of slots varies from two to six. The geometric symmetry conditions, loading conditions and boundary conditions are same as thin strip without slot and it has been maintained for all the cases of the thin strip with the slot. The dimensional implications of the different slots are depicted in Fig. 3. The dimensions considered for the slots and the name for each case of the thin strip are given in Table 1. Instead the value of width (p), the slot angle (θs) have been mentioned in the Table 1 for the thin strip with two rectangular slots. In the rectangular slot thin strips, rf refers as fillet radius. The thin curved strip with various types of slots (Rectangular, Circular and Elliptical) is shown in Fig. 4.

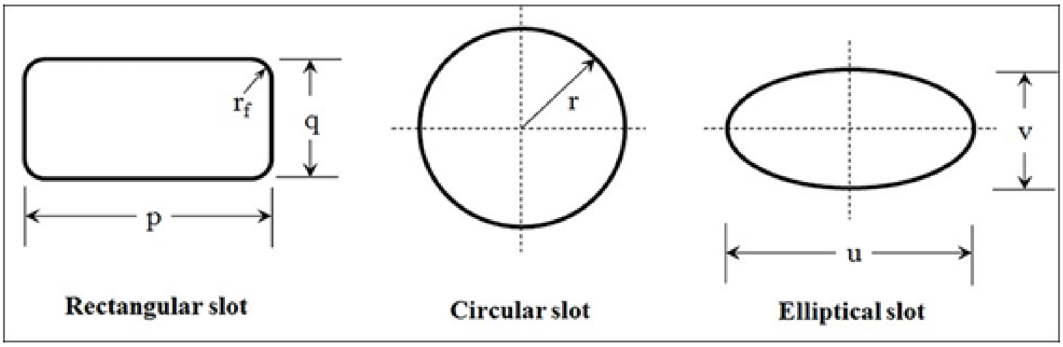

Fig. 3: Implications of slot dimensions

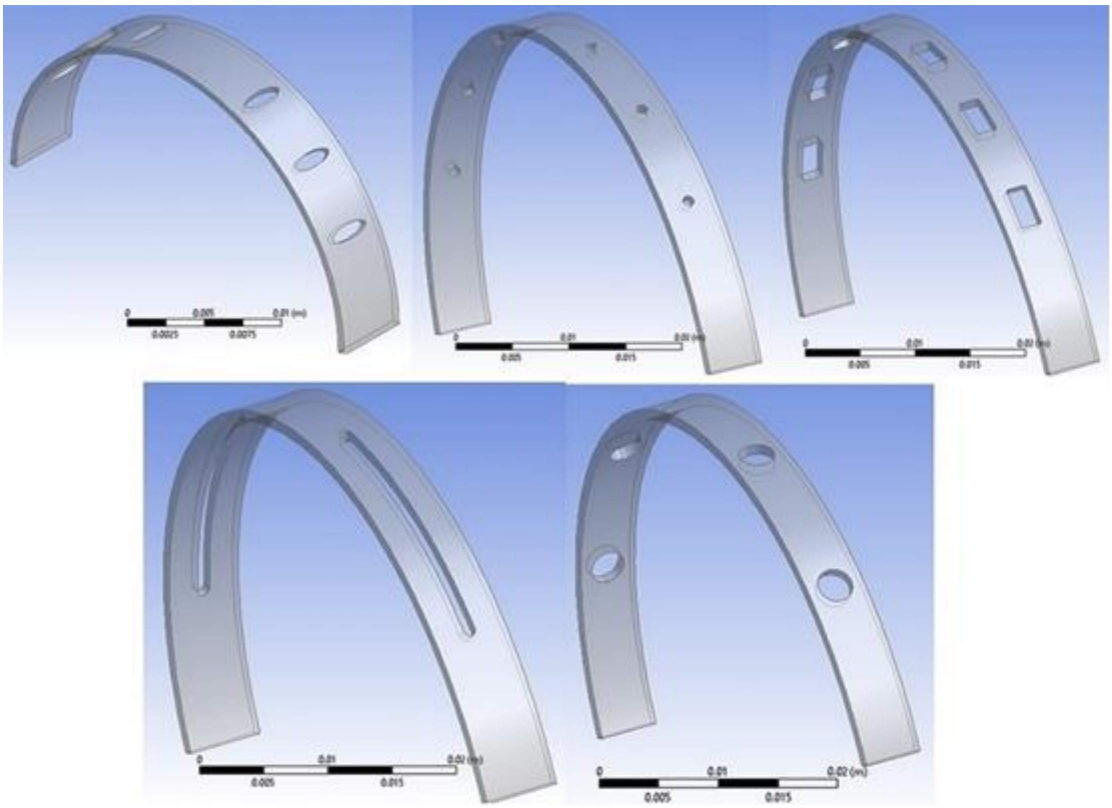

Fig. 4: Thin curved sensor with various slots

Table 1: Slot dimensions considered for Finite Element Analysis.

Type	**Number of Slots/Holes (N)**	**Dimensions considered (mm)**	**Name of thin strip**
Rectangular slot	N = 2	θs = 45°; q = 1, 2; rf = 0.25, 0.5	Strip_N_Rec_θs_q_rf
	N = 4, 6	p = 2, 4; q = 2; rf = 0.25, 0.5	Strip_N_Rec_p_q_rf
Circular slot	N = 4, 6	Radius (r) = 1, 3	Strip_N_Circ_r
Elliptical slot	N = 4, 6	u = 2,4 v = 1,3	Strip_N_Ellip_u_v

2.3 Experimental details

The thin strip of possible minimum thickness is to be proposed for the experimental study. In an experiment, there was a rift in the stiffness values at the contact position of the specimen due to the applied normal load (Vadivuchezhian K, et al., 2011). These split in stiffness values resulted in decreasing the applied bulk load and it leads to minimum relative slip at the contact position. The material has chosen to fabricate the thin strip is EN32 material since it has good elastic and ductile properties and also it is readily available. To ensure the curvature throughout the experiments, the thin strip was heat treated. Strain gauges were pasted on both inner and outer surface of the curved strip at the middle portion along the curved surface to record the strain values (Fig. 6: a). The curved portion of the strip was extended a length up to 15 mm to hold the strip during the experiments (Fig. 6: b). Initially, the thin sensor is connected with strip holder using two screws on both sides of the strip. Before using adhesives on the surfaces, all the surfaces were well polished and cleaned using acetone solution. One end of the strip along with its holder was fixed on the pad, another strip holder was pasted on the specimen using araldite adhesive. To ensure permanent fix of strip holders at both ends, nearly 1 mm thick adhesive has been used to paste the thin strip holder onto the pad and specimen. Here the bondage between pad and strip holder confirms the fixed end and the bondage between specimen and strip holder ensures that it is the end where the load is transmitted.

A fretting experimental setup with cylinder on flat configuration has been developed to identify the changes in tangential force between pad and specimen surfaces by which the changes occurred in the ratio between tangential force and normal force (Q/P ratio) concerned with numbers of cycle. During the experiments, the tangential load and coefficient of friction values for each 50 cycles have been noted and with the help of these values and normal load value the graph was plotted. The oscillatory motion on the specimen was controlled by the hydraulic actuator. The normal load was applied on the pads using threaded rod and nut arrangement which helps us to keep the constant normal load as constant throughout the experiments without any recalibration.
The testing parameters for the fretting experiments are, the normal load value of 3 kN, the experiments were last long for 500 cycles and operating frequency value of 1 Hz. The output obtained from the experiment is Q/P ratio as a function of Number of cycles and it is depicted in Figure 5. These results were verified with the results obtained from fretting experiments conducted by Vadivuchezhian (2013). These results provides considerable insight into the usage of fretting rig and thin curved sensor in fretting experiments and share a number of similarities with Vadivuchezhian (2013) findings.

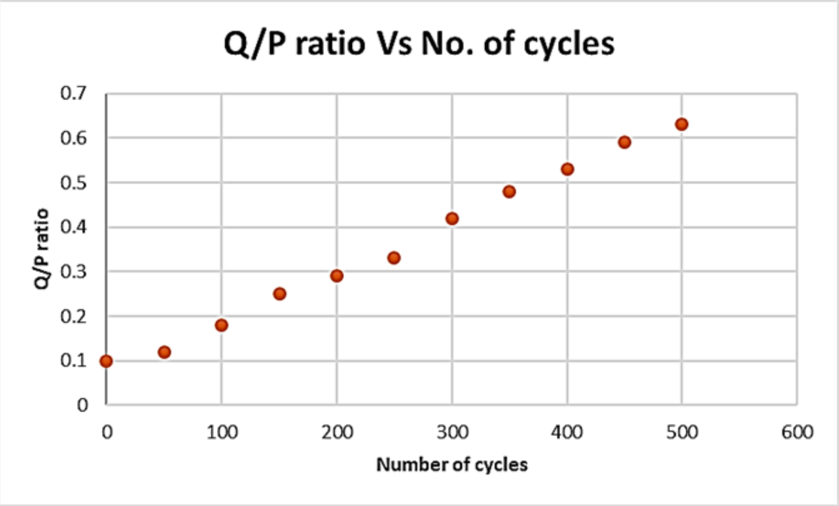

Fig. 5: Thin curved sensor with various slots

The Universal Testing Machine (UTM) with the capacity of 5 Ton have been used for this curved sensor experiment. The machine has stationery upper jaw and movable lower jaw, between them the specimen is placed. The load is gradullay applied with an load interval of 2 kg upto 50 kg using load actuator. To hold and keep the pads on either side of the specimen and applying the normal load through these pads onto the specimen, a separate rig was made and attached to the machine (Fig.7). A rig consists of two vertical plates and two separate pad holders along with two threaded rods. While doing experiments, a constant normal load was applied on both the side of specimen through pad using attached threaded rods manually. Load cells are used to measure the applied normal loads.

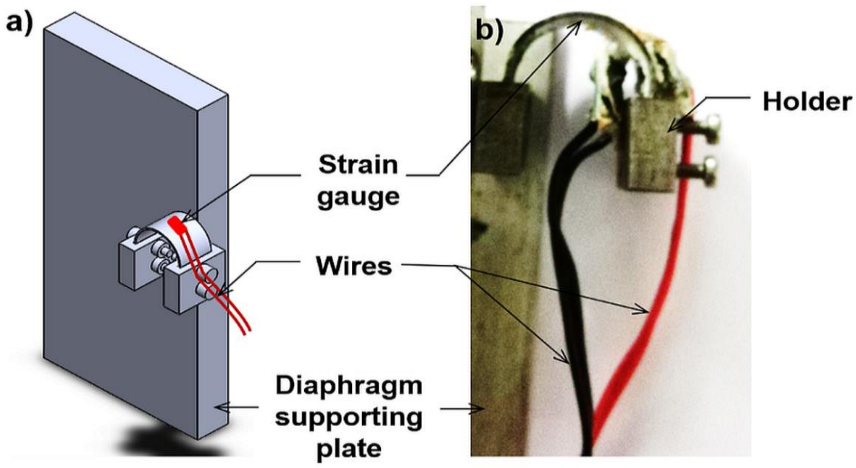

Fig. 6: a) Schematic representation of Thin curved strip and its arrangement; b) Closer view of Thin curved strip and its arrangement during experiments

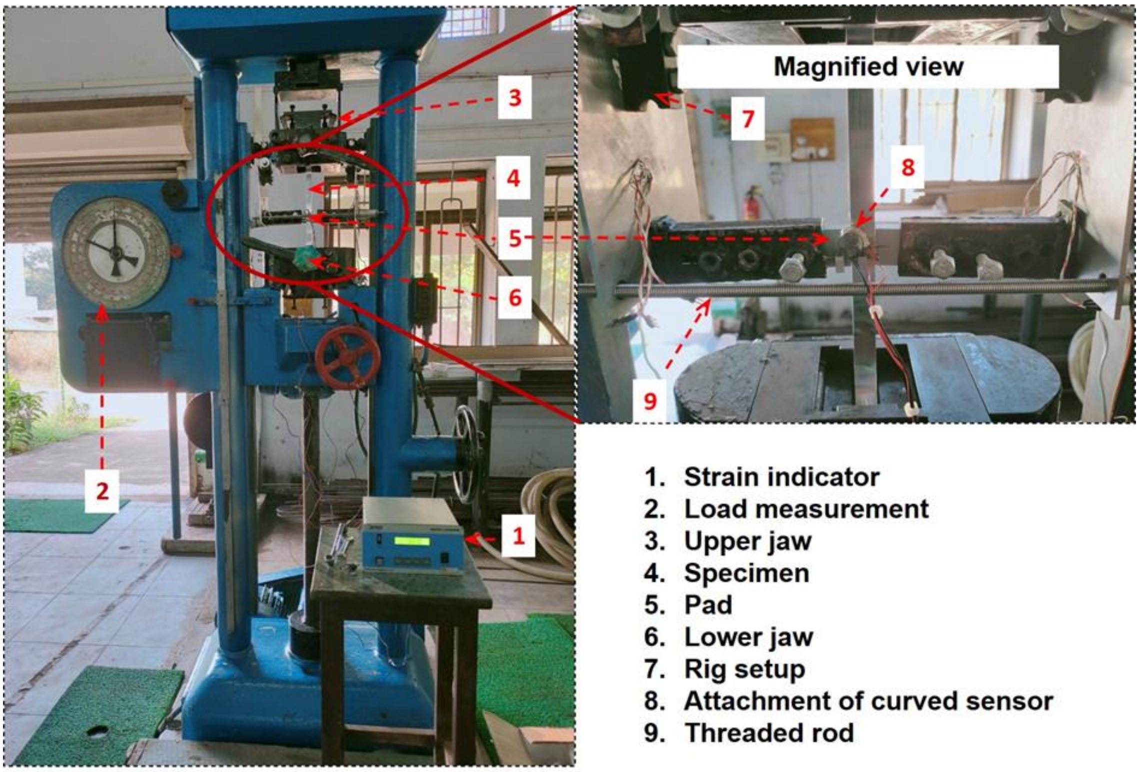

Fig. 7: Experimental setup

3. Results and Discussion

3.1 SEA Results

The curved sensor of rectangular cross-section made of spring steel was considered for analysis. The dimensions and material properties of thin curved strip material are as follows: Width (b) = 5 mm, Height (h) = 0.5 mm, Internal radius (r_i) = 7 mm, Mean radius (r) = r_i + (h/2) = 7.25 mm, and I = ($b*h^3/12$) = 0.052083 mm^4, E = 200000 MPa. Normal load (P), applied on one end of the thin strip, is 1 N and boundary condition of the other end of the curved strip has been considered as a fixed end (Fig. 2: a). By using the given values, the radius of the neutral axis was calculated as 7.2471 mm and the distance between the neutral layer and the top layer (y) of the curved strip is 0.2529 mm. By considering the above values, the SEA gives the result of δ_{max} as 0.1724 mm, δ_{mid} as 0.05747 mm and σ_{max} as 72.97 MPa.

3.2 FEA Results

The FEA results of the thin strip without the slot has given δ_{max} as 0.1687 mm, δ_{mid} as 0.05691 mm and σ_{max} as 73.832 MPa. The FEA results of the thin curved strip without slot aren't deviating more than 5 % with the SEA results. It reveals that the FE method is a viable alternative to the cumbersome analytical techniques even for the curved member analysis. Owing to the complications involved in the calculation of both moment of inertia and displacement using SEA for the slotted curved strip, the FE approach only has been considered to select a suitable slotted thin curved strip. So, the different thin curved slotted strips have been modelled and analysed using FEA. The hole in the curved strip results more deformation while applying the load and these cut outs merely produced severe stress gradient in the analysis of thin curved strip with holes. So, the stress gradient result of thin curved strip plays a vital role along with displacement result in the selection of suitable strip for fabrication. Therefore, the displacement and stress gradient results, obtained from FEA using ANSYS software, were used to select an optimised design of thin curved strip to measure contact displacement in the fretting experiments. Various investigators (Viswanathan et. al (2021), Kumaran et. al 2022) studied the mesh convergences for different models similar way a convergence study was undertaken to select the element size and no. of elements has illustrated in Fig. 8.

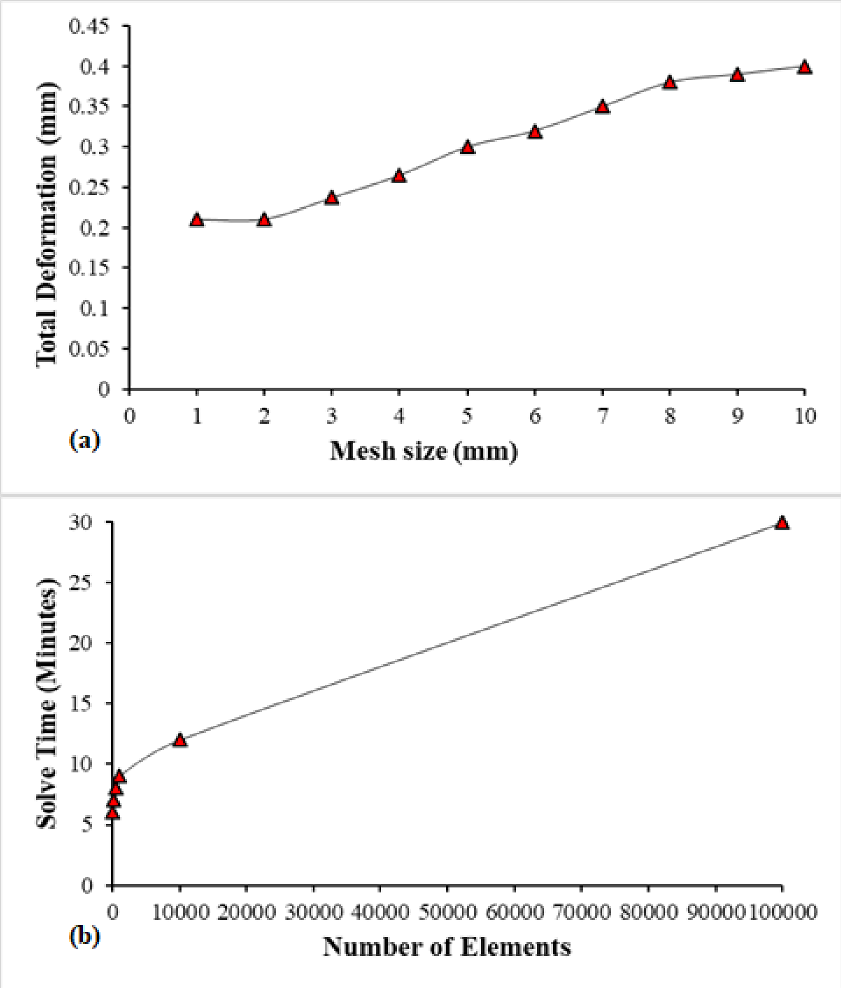

Fig. 8: Mesh Convergence study undertaken to select the element size and no of elements

Since the strip has a unit thickness and there is not much variation in the results of deformation and stress values while considering both SOLID185 and SHELL181 elements for FE analysis. Analysis with SHELL181 element produced results faster than analysis with SOLID185 elements. So, the strip had been modelled and analysed using only SHELL181 element in FE analysis. For a thin curved strip with slots, the FE analysis results are shown in Table 2.

Table 2: Finite Element Analysis results of the thin strip with slots

S.No.	Name	von Mises Stress in MPa	Deformation at middle of the strip along loading direction in mm	Total Deformation in mm
1	Strip_2_Rec_45deg_1_0.25	110.01	0.07018	0.2105
2	Strip_2_Rec_45deg_1_0.5	107.94	0.07015	0.2104
3	Strip_2_Rec_45deg_2_0.25	153.28	0.07577	0.2273
4	Strip_2_Rec_45deg_2_0.5	148.14	0.07567	0.2270
5	Strip_4_Rec_2_2_0.25	180.37	0.06958	0.2087
6	Strip_4_Rec_4_2_0.25	187.23	0.07060	0.2118
7	Strip_6_Rec_2_2_0.25	180.04	0.07030	0.2109
8	Strip_6_Rec_4_2_0.25	183.65	0.07205	0.2161
9	Strip_4_Circ_1	123.91	0.06846	0.2054
10	Strip_4_Circ_3	213.86	0.07128	0.2138
11	Strip_6_Circ_1	130.6	0.06856	0.2057
12	Strip_6_Circ_3	214.03	0.07331	0.2199
13	Strip_4_Ellip_2_1	113.84	0.06855	0.2056
14	Strip_4_Ellip_4_1	92.864	0.06873	0.2062

15	Strip_4_Ellip_2_3	245.91	0.07059	0.2118
16	Strip_4_Ellip_4_3	197.34	0.07209	0.2163
17	Strip_6_Ellip_2_1	112.81	0.06869	0.2061
18	Strip_6_Ellip_4_1	93.983	0.06896	0.2069
19	Strip_6_Ellip_2_3	249.39	0.07203	0.2161
20	Strip_6_Ellip_4_3	195.84	0.07495	0.2248

The strain gauge should be pasted on the outer side of the thin curved strip at the middle position of the strip to capture the strains at that position. So, there should not be any strain and stress gradients in the middle of the strip. For example, in Fig. 9, the von Mises stress results of the thin curved strips have been shown. The Strip_2_Rec_45deg_2_0.25 and Strip_2_Rec_45deg_2_0.5 have shown some stress gradient at middle portion of the strip than the Strip_6_Circ_3 and Strip_6_Ellip_4_3. So, the Strip_6_Circ_3 and Strip_6_Ellip_4_3 have been selected to measure contact displacement during experiments instead of the Strip_2_Rec_45deg_2_0.25 and Strip_2_Rec_45deg_2_0.5. The same process is applied to all the types of thin strips to select suitable design of thin curved strip for fabrication.

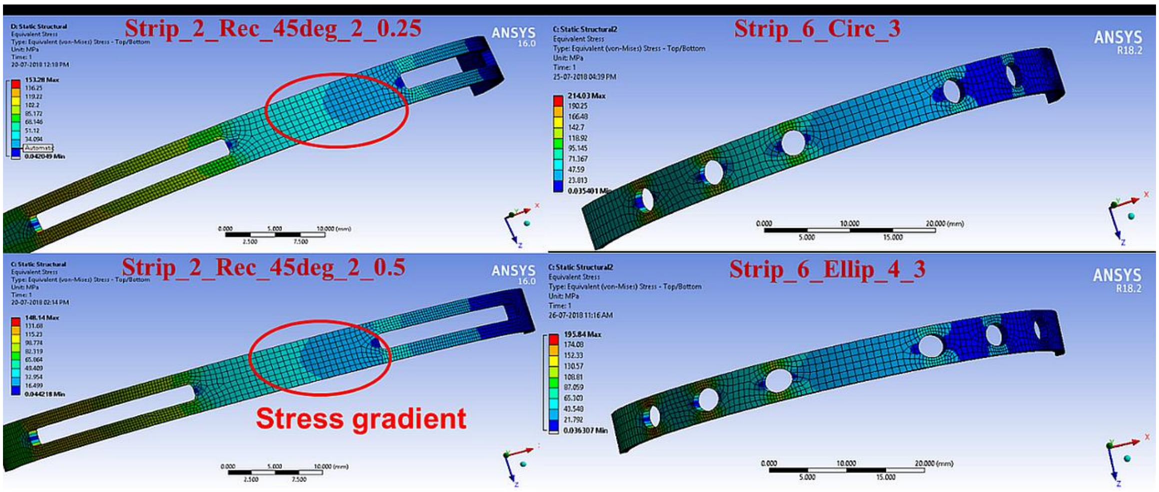

Fig. 9: Von-Mises Stress results of four different thin strip model

Of the twenty configurations considered (Table 2), configurations numbered 7, 10, 12, 16, 19 and 20 showed zero stress gradient at the middle of the thin curved strip. In the above six selected configurations, the configurations numbered 12, 16, 19 and 20 were found to be suitable for fabrication and conducting fretting experiments. The FE analysis results shown in Table 2 reveals that the increasing number and size of holes presented in the curved strip indicate that the increased in displacement and von-Mises stress values which offers the higher flexibility to the strip. The analysis confirms that there is not much significant change occurred in the results of von-Mises stress and displacement values between four- and six-holes curved strip. The reduction in area and minimum thickness of the curved strip could be the reason for the decrease in the stiffness of the curved strip. The filleted corners of the rectangular holes and the smooth surfaces of the both cylindrical and elliptical holes of the strip have limited the stress concentration effects on the thin strip.

3.3 Experimental Validation

After performing preliminary FEA, its results shown that the thickness of the thin strip has the more influence on the stiffness value. While searching for possible minimum thickness to fabricate the thin curved strip, 0.5 mm thick material was available and it was chosen for fabrication. Though the analytical study and FEA study have been performed with 1 mm thickness and 5 mm breadth, the fabrication work has been done using 0.5 mm thick and 10 mm breadth material. To convert the flat strip into a curved form, the separate mould was fabricated and heat treatment was done on the strip. The fabrication of curved strip with hole revealed that the unexpected fracture occurred on the 5 mm strip and it was found that placing a hole in curved portion is cumbersome. So the 10 mm broad strip was chosen for fabrication. The Analytical study and FEA study were done with the above-mentioned dimensions (thick (h) = 0.5 mm & breadth (b) = 10 mm) for the curved strip and their results are given Table 3. These results are helpful to validate the experimental results.

Table 3. Results of the thin strip without slots to validate experimental results

Methods used	von Mises Stress in *MPa*	Deformation at middle of the strip along loading direction in mm	Total Deformation in mm
SEA	36.16	0.02873	0.08620
FEA	36.77	0.02812	0.08401

Since the 0.5 mm thin strip is widely available and it is useful to measure very small level displacement than 1 mm thick strip (From Table 3), we have planned to conduct fretting experiment with 0.5 mm thin curved sensor to measure relative slip. Keeping the view in the complications involved in making the cut-outs in thin strip and the ability to produce lower displacement values when it is made with small thickness, the thin strip without slots was adopted to conduct experiments.

During fretting experiments, tensile load applied varied from 0 to 1060 N and tensile load was applied at the free end of the dog bone specimen using load actuator. Relative displacement at the contact interface for every increment of load was measured using curved strip pasted (attached) to pad and dog bone specimen. The strain gauge was pasted to the curved strip and strain gauge was connected to data logger and data acquisition system. The values of displacement and strain obtained by conducting fretting experiments (static load) and the outcomes of experiments are compared with finite element modelling results. The results obtained from experiment are discussed below.

The displacement value of 0.02679 mm, for 1 N load, was observed in experiments, which is less than the SEA result of 0.02873 mm (+7.24 %) and FEA result of 0.02812 mm (+4.96 %). The small variation in the displacement value obtained from the experiments is due to the following factors; the small moment occurred during the process of applying load in the experiments, the effect of adhesive and its thickness, material nature and its properties and environmental effect. The experiments confirm that thin curved strip without slot has the ability to capture the small displacement values and the fabrication of thin strip without slot is easier when compared with thin strip with slot. Hence thin curved sensor without slot can be used for fretting experiments. However, the thin strip without slots can be utilized in fretting experiments despite the complication towards in its fabrication and its ability to measure micro or nano level displacement. So, thin curved strip with slots can be used in the partial slip fretting experiments.

4. Conclusions

This article has highlighted the importance of relative slip/displacement amplitude between pad and specimen in fretting experiments and the available techniques/method used to measure the relative slip. Design of thin curved sensor/strip with and without slots was performed by using Strain Energy Approach (SEA) and Finite Element Analysis (FEA). Due to the difficulties involved in the calculation of moment of inertia, displacement and stress values, the thin curved sensor with slots was analyzed by using FEA. The main findings from the study are the thin strip with circular and elliptical slots are suitable for measuring relative slip displacement at the contact interface during fretting experiments.The advantage of this study is that these thin curved strips are able to measure the micro or nano level displacement.The evidence from the present study concludes that,

- In a curved sensor, the greater number of slots and increase in slot dimension could increase the ability to capture the micro-level displacement values and it enables them to hold higher flexibility.
- Twenty-one configurations were considered with different shapes and sizes of the slots and six configurations show zero stress gradient at the middle of the thin curved strip.
- Among these six configurations, four configurations with circular slots and elliptical slots were found suitable for the fabrication of thin curved strip and for measuring contact displacement during fretting experiments.
- Thin strip with rectangular slots was not suitable due to the high-stress gradient at the middle of the strip.
- Small variation between the displacement value obtained from experiments and that from analytical approach and numerical approach is less than 7.3 % and it can be reduced by focusing on factors such as the process of applying the load, selection of adhesive and its thickness, selection of material and environmental conditions.
- Use of thin strip without slot has been verified when displacement value observed experimentally was compared with that of SEA result and FEA result. This validates the use of the thin strip without slot for conducting fretting experiments.
- Even though thin curved strip without slot ensures its use in fretting experiments, thin curved strip with slots can be considered to be very useful in partial slip fretting experiments, due to its ability towards

the measurement of micro or nano level displacement, despite the complications involved in its fabrication.

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