COMPUTATIONAL AND EXPERIMENTAL INVESTIGATION OF FATIGUE LIFE UNDER FRETTING CONDITIONS

Miroslav Španiel[a], Josef Jurenka[a], Jiří Kuželka[a], Martin Nesládek[a], Jan Růžička[a]

[a] Czech Technical University in Prague, Fac. of Mech. Eng, Technická 4, 166 07 Prague, Czech Republic

Abstract. The fretting fatigue is special type of fatigue damage which takes place usually near contact interface of bodies with no or small relative movements. There are three basic factors with major influence: field of stresses at the vicinity of contact interface, partial slipping of contact surfaces and friction between contact areas. Contact conditions can be divided into three ranges regarding magnitudes of partial slips: the stick, slip and gross sliding range. Fatigue life considerably decreases in range of partial slips. The paper summarized in this brief text deals with research of phenomenological fatigue criteria applied on contact fatigue under fretting conditions.
Evaluation of fretting fatigue damage based on phenomenological criteria calibrated with relatively small set of experiments is objective of presented research. Verification and/or formulation of new fretting fatigue criteria have to be based on reliable experimental and computational results. In practice, quantities needed for fretting fatigue evaluation, including contact relative slips, are usually calculated using finite element method. Computational evaluation of contact conditions is strongly dependent on phenomenological description of friction. There are several commonly implemented models of friction in finite element codes. These models use experimentally determined parameters, as friction coefficient that may be dependent on specific conditions differing from experimental ones. Moreover, numerical enforcement of law of friction may be chosen from several possibilities in Abaqus FE code used in presented research. That is why we tried to verify numerical model of fretting experimental setup.
The displacement and strain field measurement at the vicinity of contact interface is very complex and difficult. Some of the optical measuring methods seem to be one of the possible ways to identify these fields. Optical measuring system DANTEC DYNAMICS Q-450 employing digital image correlation method for displacement field evaluation was used to verify numerical model of friction conditions. In order to test the system under similar conditions to fretting fatigue the flat notched specimens were treated.
Numerical analysis using finite element method was used to determine stress fields and relative slips in contact interface of specimen in experimental setup. These quantities serve as input to several fatigue criteria that are to be compared each to other and evaluated.

1 INTRODUCTION

Fretting fatigue can be defined as fatigue damage near contact interface accelerated due to small relative tangential movements of contacting surfaces. Stress field at the vicinity of contact interface, friction and partial slipping of contact surfaces are commonly evaluated as factors having significant influence on local damage resulting into the crack initiation. Fretting fatigue occurs particularly in typical machines parts as pressed joints, turbine blades lock joints, slot couplings, etc.

1.1 The fretting phenomenon

The values of relative slips of the contacting surfaces are widely used for description of the contact regimes under the fretting conditions [1]. Regarding the slip range, those regimes are: the stick regime with the slip magnitude up to 3 μm, the partial slip regime with the slips between 3 to 50 μm, and the gross sliding where the slips are more than 50 μm.
It should be noted that the relation between the slip magnitudes and the fatigue life is not monotonic. One can observe a dramatic decrease in the partial slip regime. This state is specific for sticking in the centre of the interface and for slipping of both surfaces around the contact edges – see figure 1. This is the area of the most severe material damage which can, together with high stresses, act as “the weakest link” accelerating fatigue crack nucleation.
The decrease of the fatigue life in the partial-slip regime is followed by a rapid increase in the phase of transition to the gross sliding. This is due to intensive material erosion which removes crack nucleuses. Note, that from practical point of view the exposed component will be damaged with abrasion instead of fatigue in such a case.

All the three above mentioned factors – stress, friction and contact slips – are closely dependent and in the real structures they change during their life-time.

1.2 Fretting damage

Due to the multi-axial stress state in the fretted contact, conventional multi-axial fatigue criteria based on the critical plane estimation are widely used to predict the place of the initiation and the direction of the initial crack growth. Relations for conversion of some of these criteria to the number of cycles can be found e.g. in [3].

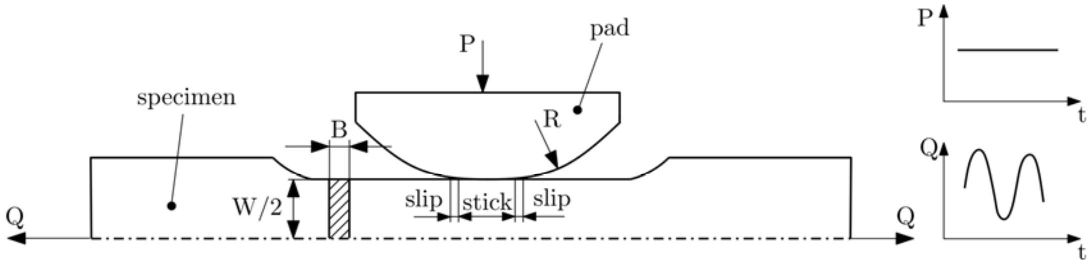


Figure 1. A typical laboratory configuration for simulation of partial-slip fretting conditions (cylinder on a flat contact geometry).

In the last decade, some authors have been trying to adopt the simulation procedure including surface wear based on the Archard's formula [4] or the dissipated energy concept [5]. Nevertheless, incremental estimation of wear together with damage cumulating is still unfeasible for real structures.
Another possibility how to improve the results of conventional fatigue criteria is to incorporate certain correction with respect to the fretting wear. Ideally, it should reflect the values that cause surface damage, i.e. relative slips and surface shear stress. Ding et al. [6] introduced a simple parameter D_{fret2} correcting the multi-axial SWT criterion. According to the authors, the main contribution of D_{fret2} is that SWT can now handle the increase in the fatigue life in the transition domain between the partial and gross slips.
The goal of the presented project is to verify specific multi-axial fatigue criteria by the fatigue tests. New testing equipment was developed for this purpose and a digital image correlation method was newly employed in this field in order to calibrate the friction in FE model.
Evaluation of fatigue damage under fretting conditions based on phenomenological criteria is target of presented research. Verification of fretting fatigue criteria have to be based on reliable experimental and computational results. Quantities describing local material loading as stress field, contact slips, etc., the measurement of which is very difficult, are in practice often calculated using finite element method. It is dependent on phenomenological description of friction. That is why we decided to verify and identify numerical model of experimental setup from the point of view of friction.

2 FRETTING EXPERIMENTAL SETUP

2.1 The experimental setup description

The concept of the original setup for testing of fatigue under fretting conditions developed in the scope of an acknowledged project was briefly introduced in [7]. It was designed as a single dog-bone specimen in contact with two cylindrical pads causing fretting. The main advantage of the cylinder on flat contact geometry is the possibility of its use in standard fatigue testing machines. The equipment designed for the experiment is shown in figure 2. The specimen is vertically clamped in the jaws of the testing machine and axially loaded by a time-varying force. The loading frequency corresponds to the natural frequency of the system which reflects the mass of the machine and the stiffness of additional experimental equipment and the specimen. The normal contact force acts in the horizontal direction which is perpendicular to the axial cyclic loading. This force is kept approximately constant during a single test.

2.2 Development, tuning and modifications of experimental equipment

Preliminary tests had shown some weaknesses of experimental setup. The loading conditions of the first three fatigue experiments that have been carried out are provided in Table. Numbers of cycles to crack initiation N are also shown. They were estimated based on the stiffness decrease in the experimental setup. The axial loading frequency was about 100 Hz. The material of the specimens was Cr-Ni-Mo-V martensitic steel with the plain fatigue strength in reversed tension f_{-1} = 485 MPa. The cross-sectional dimensions were thickness B = 6 mm and width W = 20 mm (see figure 1). Fretting pads with the radius R = 200 mm were used.
Relatively high scatter can be observed from these data. Especially the difference between tests no. 1 and 3 reflects certain auxiliary influence.

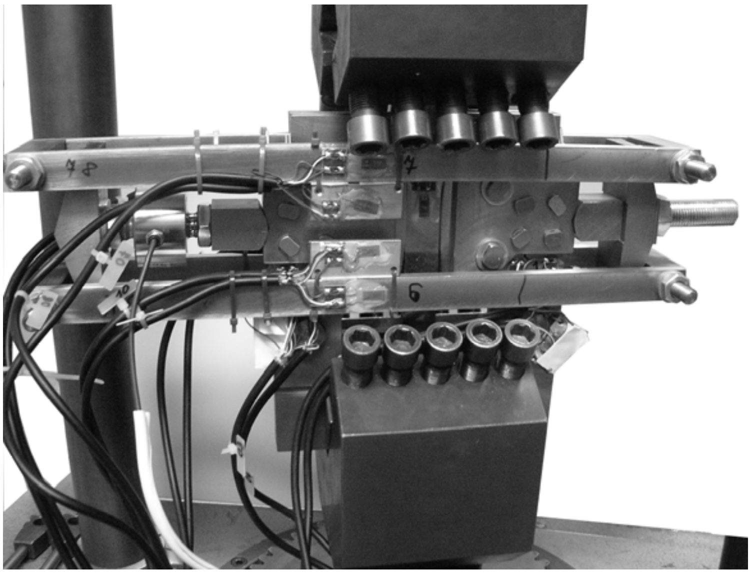


Figure 2. The setup for the fretting fatigue testing. The equipment is clamped in the electromagnetic pulsator AMSLER.

Fatigue crack initiation always took place on the top contact edge–see figure 3 and figure 4 which are vertically oriented according to the position of the specimen in the testing rig (figure 2). This fact is in line with the general assumptions that the crack initiation usually occurs in the slipping area of a contact in the partial-slip regime. This is also the place of the most severe damage of the exterior faces as can be observed from the pictures of the surface relief. By contrast, mild damage of the central contact area where sticking occurs can be seen.

Table I. Loading conditions and number of cycles to crack initiation in the fretting experiments.

Experiment no.	$Q_{amp.}$ [N]	Q_{mean} [N]	P [N]	N [-]
1	14	15	15	2 849 000
2	14	15	5	1 577 000
3	14	15	15	1 676 000

Relief of both contact surfaces of each specimen was scanned by a digital microscopic camera with 2Mpix resolution. Panoramic pictures, like those in figureFigure 3 3 and figure 4, were then obtained by merging more than 100 single scans.

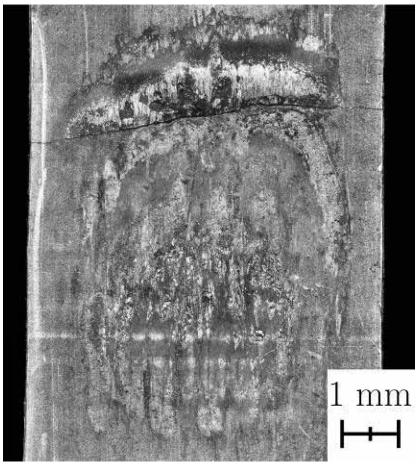


Figure 3. Detail of worn contact surface of the specimen after fretting test no. 1 – side A.

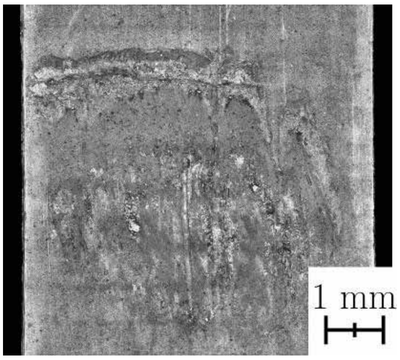


Figure 4. Detail of worn contact surface of the specimen after fretting test no. 1 – side B.

Contact loading was concentrated mostly in the centre of the specimens and fretting pads. In some cases, the contact area was shifted from the centre towards the edge of the specimen. This violates the assumption about the uniform load distribution between both specimen edges that was also proved by the FE models.
Regarding the above observations of improper contact loading distribution, revision of the testing apparatus was done in order to reveal sources of this problem. Severe inaccuracy in the surface finish of the fretting pads was detected by

roughness tester. In the transverse direction, the measured surface contour was curved instead of being straight. To circumvent this problem, a more precise finishing was performed on a CNC machine.
Another design modification was done on the fretting pad bearing surfaces—see figure 5 and figure 6. A detail of the pad installation in the testing apparatus is shown in figure 7. Rigidity of the original alternative did not allow rotation of the fretting pads which could eliminate the initial non-parallel setup of the contact surfaces. That is the reason why additional chamfers were manufactured. Together with lateral gaps as shown in figure 6, this arrangement is capable of compensating the initial inaccuracies given by manufacturing.

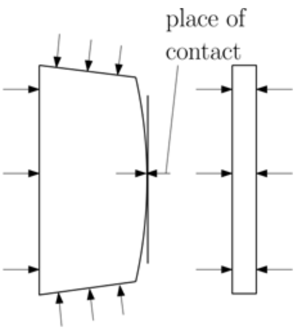


Figure 5. The original fretting pad geometry with flat side faces. The arrows show where the pad was connected to the rest of the structure.

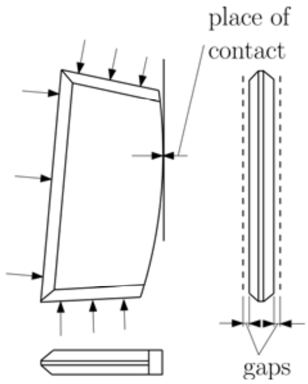


Figure 6. The modified fretting pad geometry with additional chamfers and lateral gaps allowing better match with the contact surface of a specimen. The rotated position enables a one-off reuse of the same pad.

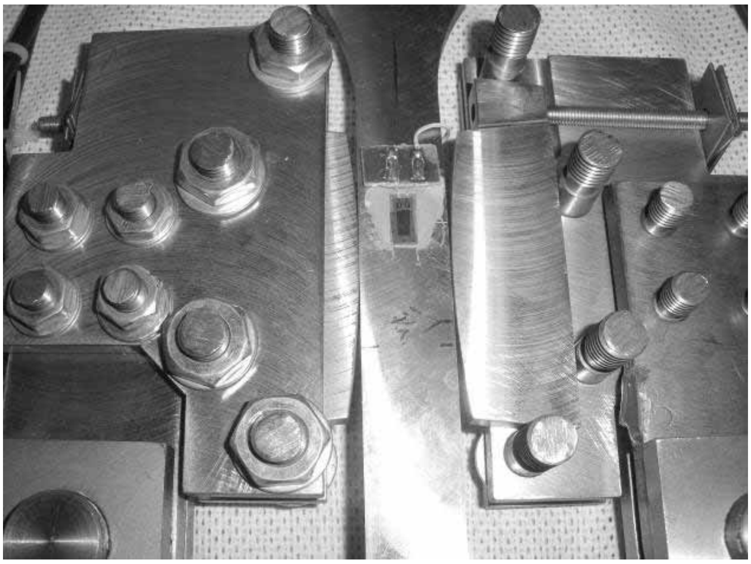


Figure 7. Detail of the fretting pad installation in the experimental equipment – the original configuration without chamfers.

Usually no fatigue cracks occur on the pads after the experiment termination. The contact surfaces can then be renovated by grinding and after that the pads can be reused. Since this is a costly operation, the following simple modification of the fretting pad installation was introduced. Both pads are now fixed in a moderately rotated position (compare figure 5 and figure 6). Due to this, the contact area is shifted horizontally on the fretting pads which enable their one-off reuse when they are installed upside down. The beneficial effect is that it will halve the time losses and expenses for their renovation.

3 EXPERIMENTAL AND COMPUTATIONAL DETERMINATION OF CONTACT SLIPS

3.1 Relative slips measurements

The Dantec Dynamics Q-450 optical system was used for relative displacements measurements. Since displacements in order of μm had been measured at high frame rate, the demands on pattern quality and lighting were quite high.
Regarding 1Mpix resolution of CCD chip the objective and extension tubes were used to achieve spatial resolution of approximately 8μm/pix with the field of view of about 5x8 mm. The viewed surfaces were clothed in a very fine contrast stochastic speckle pattern created with airbrush considering the recommendations in [7]. Two special high

frequency lamps with 1kW power were used for sufficient lighting. The images of the vicinity of the contact interface between the specimen and pad were recorded by a high speed NanoSense Mk III camera with the frequency of 2 kHz (corresponds to 20 images per loading cycle).Data were acquired during a relatively short period of about 50 cycles after every 200 thousand cycles. The data related to the sequence of images of the contact interface, traction force transmitted by pads and pressure force P were gathered.

The acquired sets of image sequences were processed in the commercial image correlation software Istra 4-D. The displacements were evaluated in a 0.1 mm (12 pix) equally spaced grid. Each grid point corresponds to a subset 0.2x0.2 mm (25x25 pix). The obtained results were further post-processed by Matlab scripts.

The point with maximal contact pressure (and thus the centre of the contact area) was estimated on the basis of displacement field in case of pure pressure loading of 10 kN magnitude. At this point, a coordinate system for relative slip evaluation was introduced (figure 8).

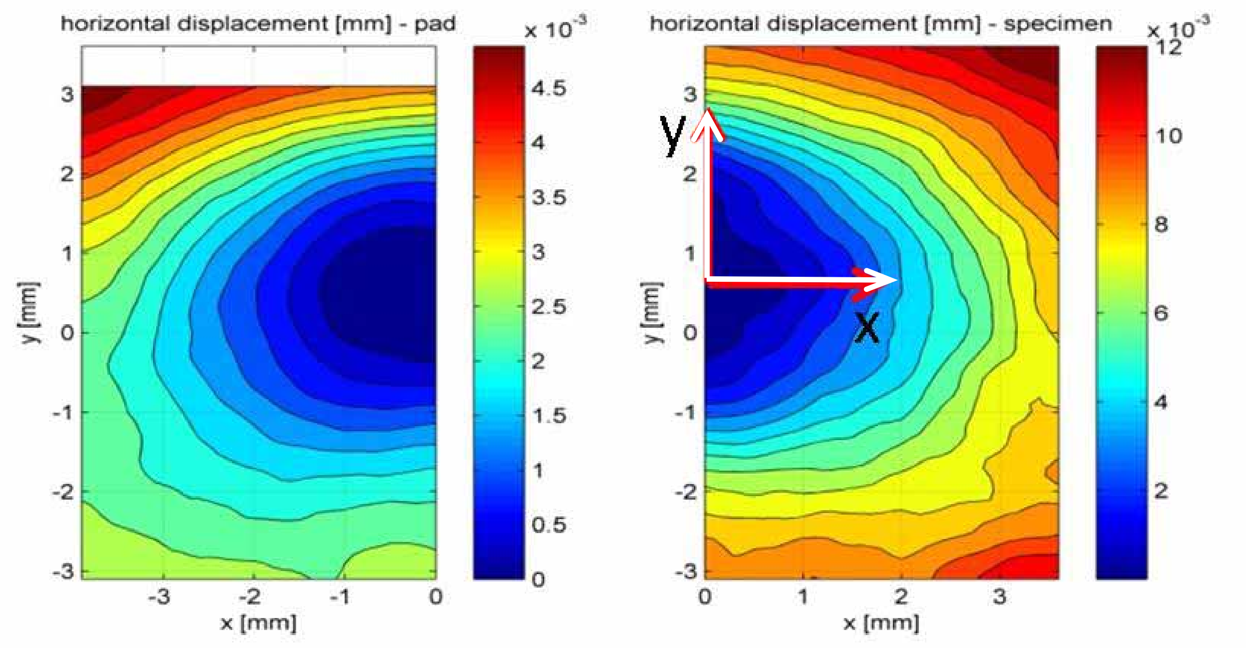


Figure 8. Experimentally measured time history of relative slips in different locations in the contact interface for 10 kN pressure loading.

.

The Hertz contact theory was applied for the estimation of the contact area width. The relative slips were computed as a difference between the displacements along a line near the contact edge on the specimen and the pad. The time behavior of the contact slips on the top, in the middle and on the bottom of the contact area is shown in figure 9. The changing character of slipping from the more loaded side (top) to the less loaded side (bottom) can be observed.

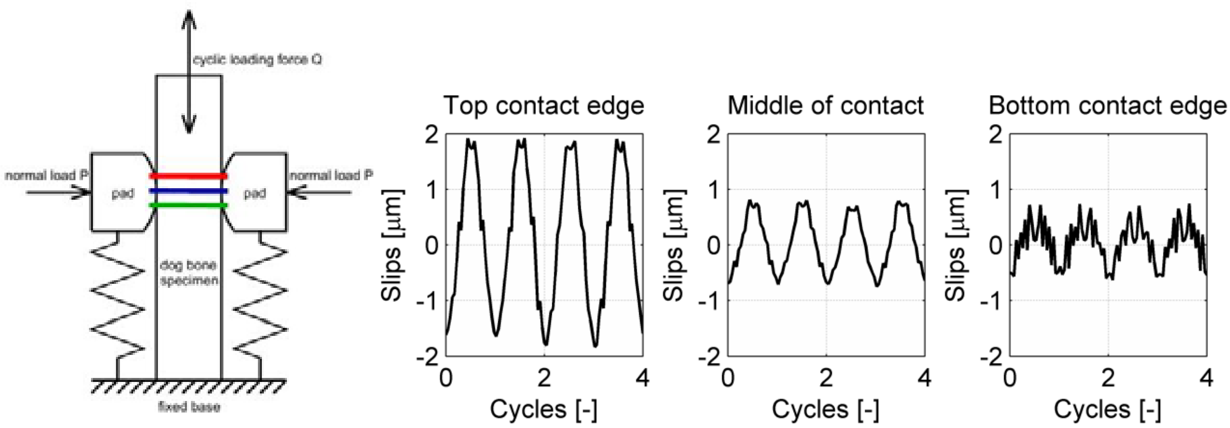


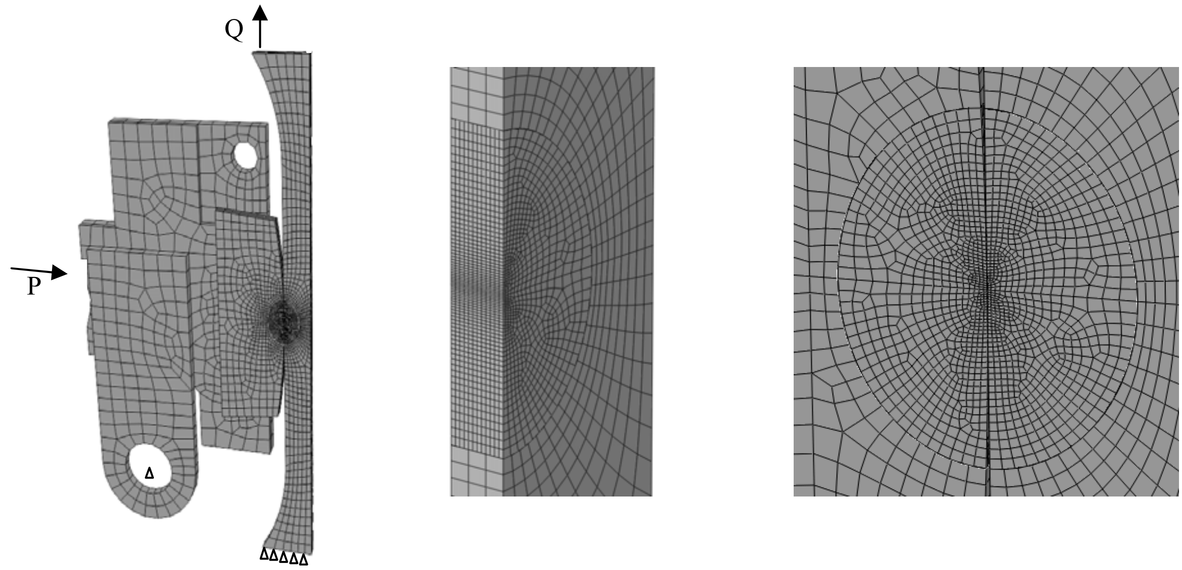
Figure 9. Experimentally measured time history of relative slips in different locations in the contact interface for 10 kN pressure loading.

Several measurements were performed in order to acquire reliable values of the contact slips for further FE model calibration. As can be seen from the time history of the relative contact slips, this quantity has a changing character with respect to the position along the contact.

3.2 Computational modeling of relative slips

To obtain required input data for the fatigue criteria, a 3D FE model of the testing apparatus was assembled – see figure 10 – and analyzed. The commercial FE solver Abaqus was used for the numerical simulation which was divided into several computation steps reflecting pressure and axial preload (static) and application of axial cyclic loading.(explicit dynamics). The material model was first assumed to be linear elastic. In the final analysis the plasticity was included as well. The geometry was discretised by linear hexahedral continuum elements. The smallest element edge in the contact area was approximately 85 μm–see figure 10.

A proper modeling of the contact friction has a significant effect on relative slips determination. Contact slips is the significant parameter of fretting fatigue evaluation. The friction coefficient used in the fretting simulations is usually higher than in a conventional contact and should reflect its change during the life-time. FE solver Abaqus contact algorithms adopt several computation techniques. In our model, surface-to-surface discretization, finite-sliding tracking approach and hard contact with the Coulomb friction was applied.



Global view | Detail of the specimen mesh. | Contact area mesh (the specimen is on the right).

Figure 10. Finite element model of the testing apparatus.

3.3 Comparison of experimentally an computationally determined contact slips

At first, a proper quantity for comparison of the experimental and numerical results must be chosen. The choice of the slip amplitudes along the contact area was found misleading for this purpose. According to the experimental results, this quantity is not convenient since approaching the bottom edge of the contact the slipping process becomes more stochastic. Moreover, the amplitudes in the middle of the contact are as high as on the bottom.

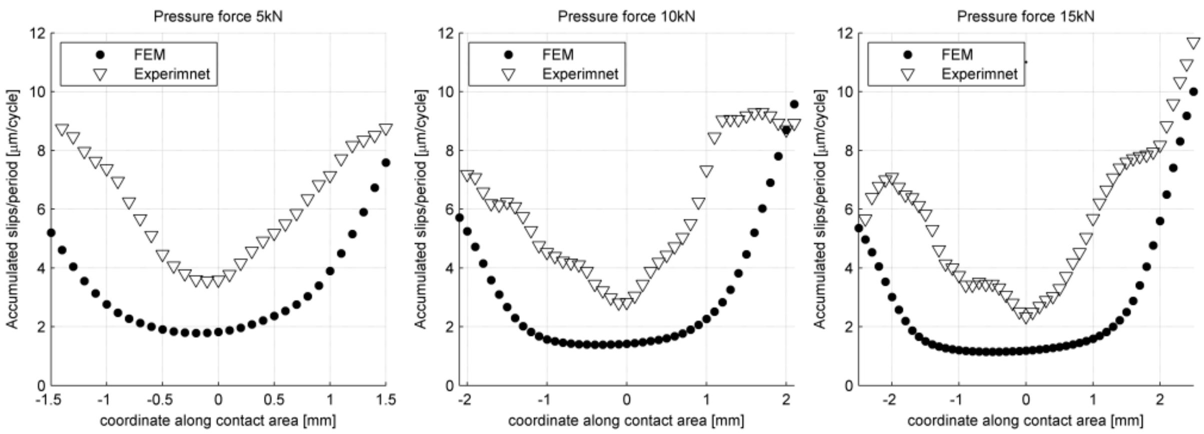


Figure 11. Accumulated relative slips per single cycle period along the contact interface for 5, 10 and 15 kN pressure force P. Comparison of experimental and numerical results. Early FE model.

When using a more integral quantity a better conformity can be expected. Accumulated slips per single period appear to be a more suitable measure. This quantity has a clearer physical meaning than the slip amplitudes and can be used for experimentally and computationally determined contact slips comparison.
In figure 11 the early results are shown. The correspondence was not satisfactory. The FE model was simplified both from the point of view of assembly constraints and material. Improved FE model including all parts of experimental setup connected mostly with contact conditions and elastic-plastic material provided us with better results that correspond with measured accumulated slips from the point of view of shape. After calibration of friction coefficient the FE model was accepted as corresponding with reality. Experimentally and computationally determined accumulated contact slips in dependence on the position in contact area are plotted in graph on figure 12.

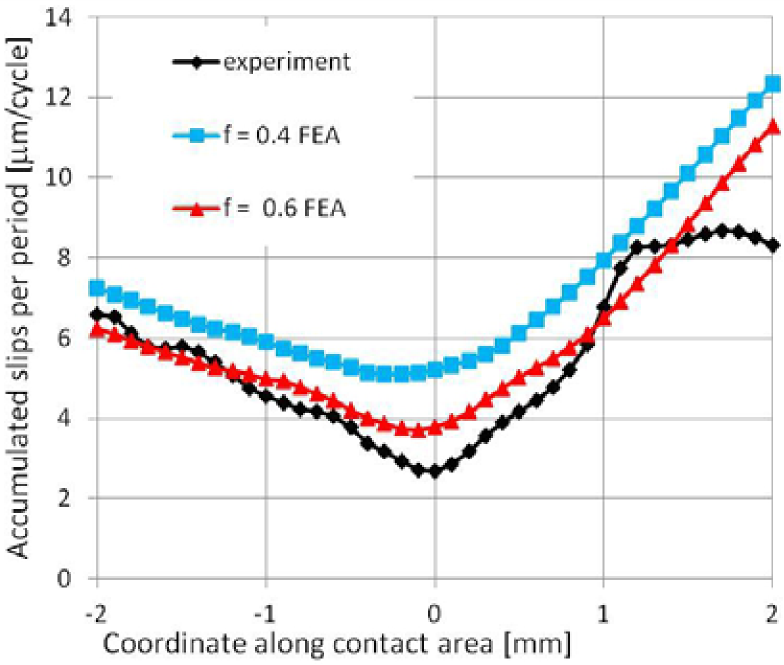


Figure 12. Accumulated relative slips per single cycle period along the contact interface for 10 kN pressure force P. Comparison of experimental and numerical results. Final FE model.

4 CONCLUSION

- Experimental setup for fretting fatigue tests was designed and manufactured. Based on presented results of the preliminary experiments under fretting conditions which revealed improper distribution of the contact loads several modifications in the equipment design were performed. These are mostly related to geometry and installation of the fretting pads. Subsequent tests proved that the new design has the capability to distribute the contact loads over the whole specimen width as was originally expected. This should result in a reduced scatter in the fatigue experiments.
- Using this tuned experimental setup several measurements of contact slips were performed in order to acquire reliable values of the contact slips for further FE model calibration. The Dantec Dynamics Q-450 optical system employing digital image correlation method was found acceptable for this purpose. As can be seen from the time history of the relative contact slips, this quantity has a changing character with respect to the position along the contact. This behavior cannot be simulated by a relatively cheap steady-state numerical solution. An explicit dynamic formulation of the problem and complex finite element model were found necessary to obtain acceptable correlation of accumulated contact slips with reality which is an important for further research.
- By varying the parameters of the numerical model (especially friction) a better correlation can be expected between the numerical and experimental data. In this case the Coulomb friction with the coefficient 0.6 was calibrated. It reflects the average tribological conditions in the contact.
- Most of fretting fatigue tests was done but not fully evaluated until now. We continue with fatigue criteria under fretting condition testing and comparison based on both these tests and data provided by the calibrated 3D a 2D finite element models described in this paper.

5 ACKKNOWLEDGEMENT

This project is kindly supported by GAČR grant no. 101/09/1709.

6 REFERENCES

1-Hoeppner, D.W., Fretting fatigue case studies of engineering components, *Tribology Int.*, 39, pp. 1271-1276 (2006).

2-Vingsbo O., Soderberg, S., On fretting wears, *Wear*, 126, pp. 131-147 (1988).

3-Navarro, C., Muñoz, S., Domínguez, J., On the use of multiaxial fatigue citeria for fretting fatigue life assesment, *Int. J. of Fatigue*, 30, pp. 32-44 (2008).

4-Madge, J.J., Leen, S.B., McColl, I.R., Shipway, P.H., Contact-evolution based prediction of fretting fatigue life: Effect of slip amplitude, *Wear*, 262, pp. 1159-1170 (2007).

5-Mary, C., Fouvry, S., Numerical prediction of fretting contact durability using energy wear approach: Optimisation of finite-element model, *Wear*, 263, pp. 444-450 (2007).

6-Ding, J., Houghton, D., Williams, E.J., Leen, S.B., Simple parameters to predict effect of surface damage on fretting fatigue, *Int. J. of Fatigue*, 33, pp. 332-342 (2011).

7-Kuželka, J., Chlup, H., Jurenka, J., Španiel, M., Fatigue degradation in the vicinity of contact interface under fretting conditions, in *Proceedings of Experimental Stress Analysis,* Velké Losiny, Czech Rep., June 2010, pp. 201-208. ISBN 978-80-244-2533-7.

8-Sutton A.M., Orteu J. and Schreier W.H., *Image Correlation for Shape, Motion and Deformation Measurements* (Springer, New York, 2009). ISBN 978-0-387-78746-6.