Slightly helicoidal crack versus planar transverse crack effects in rotating shafts

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ABSTRACT. *The static elastic behaviour of a slant or helicoidal cracked shaft has been analysed by means of a 3D non-linear model, calculating deflections in different load conditions. This kind of crack can develop in rotating shafts loaded by huge torsion and bending loads. The results are compared to those of the more common transverse planar crack. The peculiarity of the behaviour of shafts affected by slightly helicoidal cracks, which are reflected also in the dynamical behaviour of rotating cracked shafts, is emphasized .*

INTRODUCTION

. In literature the dynamical behaviour of a shaft with a slant crack, a crack which has developed along a helicoidal path with an angle of 45°, is analysed [1, 2, 3]; probably the study was triggered by the detection of this kind of defect in an industrial machine, but the failure has never been reported in public literature. In these studies the slant crack is assumed to open and close periodically accordingly to the direction of a sinusoidal torque which is assumed to be applied to the shaft. The bending stiffness of the shaft is changing from a maximum with closed crack to a minimum with open crack. The bending vibrations are then modulated by the torsional frequency.

The crack which is studied in this paper has developed along a helicoidal path with an angle of 6° only on the outer surface of the shaft. The aim of this analysis is to evaluate the behaviour of a shaft with this type of crack during full load operation. A static bending moment due to static loads such as the weight in horizontal axis machines and the bearing reaction forces, as well as a static torque is applied to the rotating shaft. In order to study the behaviour of the shaft affected by a slight helicoidal crack, a reduced scale model specimen has been designed, suitable to be used also for laboratory experimental tests. This research has been performed in cooperation with EDF (Electricité de France) R&D, where also some experimental tests on a specimen affected by helicoidal cracks have been performed. The specimen has a diameter of 70mm, the crack which has been analyzed in the present study has a depth of 30 mm, and an angular extension of 240°. The angle of the helicoidal curve of the crack on the cylindrical specimen surface with respect to a plane orthogonal to the cylinder axis is equal to 6°. This angle increases when moving from outside of the shaft to the inside, closer to the crack tip.

Different rotating loads have been applied to one end of the cracked specimen clamped at its other end, and the so called breathing behavior (the opening and closing mechanism) and deflections have been evaluated for the different angular positions of the loads with respect to the crack. The effect of the applied constant torque combined to the rotating bending load (assuming a reference system fixed on the rotating shaft), which are responsible for generating the helicoidal crack, is analyzed in detail. Shear forces are neglected since in the position where the crack has developed in the steam turbine shaft (at mid span in between its bearings), the shear forces are supposed to be negligible. Dynamical loads are disregarded in this study. In industrial machines the static torque during normal operating conditions overcomes completely the dynamic torque components, therefore the direction of torque does not change in this full load condition. In these conditions the breathing behaviour is determined by the static bending and torsion loads only. The breathing behavior determines the collaborating surface of the crack, which defines the stiffness of the cracked beam, and therefore also its deflections when loads are applied to the cracked beam.

In order to emphasize the effect of the crack and to highlight the differences in its static elastic behaviour of the helicoidal crack with respect to the transverse crack with the same shape and extension, the deflections of the un-cracked specimen have been subtracted from the deflections of the cracked specimens, and these differences are compared in the same diagrams for the helicoidal and for the transverse cracks.

DESCRIPTION OF THE MODEL

The model of the crack surface has been created generating on the cylindrical specimen a separation surface obtained by moving a radial segment along a helicoidal path. The two parts of the cylinder separated by the separation surface have then been meshed by an automatic procedure. The final configuration of the crack is then obtained by connecting corresponding nodes of the two parts on the separation surface there where the crack has not arrived during its propagation, re-establishing the material continuity, and imposing the usual contact conditions on the remaining nodes (Fig. 1). The accuracy of the numerical results is expected to be good enough for calculating deflections due to applied loads, but will not be sufficient for checking stress intensity factors or for predicting propagation speed of the crack. The friction coefficient in the contact areas of the crack surfaces is considered equal to 0.4.

The specimen has a length of twice the diameter, but has also an extension length: loads are applied only to this extremity so that stresses and strains in correspondence of the crack and of the “measuring section”, where displacements and rotations are evaluated, will be unaffected by local distortions due to the applied loads.The specimen is clamped at its other extremity. This configuration has been meshed automatically, which has the advantage of simplicity but has the disadvantage that the position of the nodes of the mesh on the two surfaces of the crack do not correspond each other. The consequence of this fact is that the interpolating surfaces which connect the nodes, are not exactly the same. Fig. 1 shows also the superposition of master and slave nodes of the cracked surface. When contact occurs between the two surfaces, the contact is not continuous and some points of these surfaces are not in contact. This does not affect the overall deflections, but makes the breathing mechanism analysis less accurate. On the other hand the experimental investigation on the breathing behavior of transverse cracks [4] has shown that, in closed crack configuration, only a smaller part of the cracked surface is really in contact. Therefore also in real cracks the contact does not occur in all points of a crack surface.

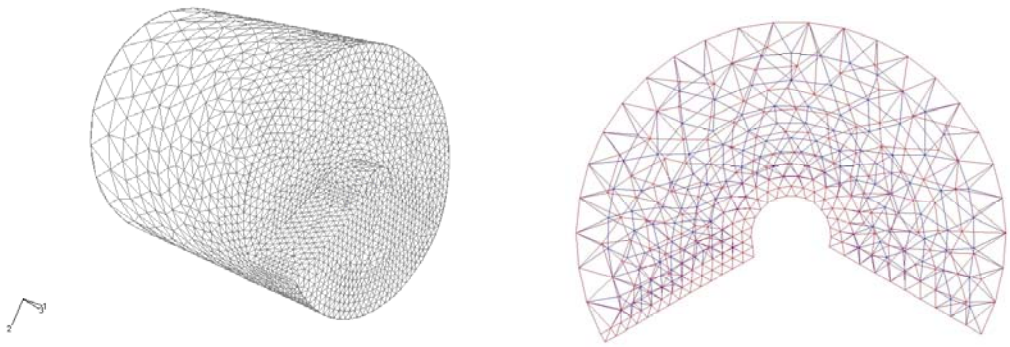


Figure 1 Mesh (left) and master and slave nodes (right) on the cracked surface

RESULTS

Preliminarly the contact conditions in the helicoidal crack have been investigated determining the breathing behaviour. Taking into account the scale ratio of the specimen to a real machine and the loads on a real machine in operating conditions at full load, the scaled loads are following:
Bending moment Mb = 600 Nm and Torsion moment Mt = 1200 Nm

Breathing behaviour

Fig.2 shows the 3D breathing behaviour for the cracked shaft loaded by full bending and torsion load. In order to have a deeper insight in the behaviour of helicoidal cracks and check the linearity of the overall behaviour of the cracked specimen, several different load conditions have been applied to the cracked specimen, and the deflections have been calculated. All the different load conditions have been applied also to a planar transverse crack with the same angular extensions in order to have a reference situation to which the results of the helicoidal crack can be compared. It should further be remainded that only the effect of the crack is shown in all the figures. From the cracked shaft deflections the un-cracked shaft deflections are subtracted.

Figure 2 Breathing behaviour of fully loaded cracked shaft: load rotated by 60°, 90°, 120° and 150°. In dark zones contact between crack faces occurs.

Deflections

First the effect of torsion alone (no bending) has been analysed. This is shown in Fig. 3 and 4 for all the degrees of freedom, in which the maximum differences have been found. Vertical displacement, rotation around horizontal axis, axial displacement and torsional rotation are vanishing small for the planar transverse (flat) crack but reach consistent values for the helicoidal crack. The deflections according to the remaining degrees of freedom are smaller for the helicoidal crack than for the flat crack.

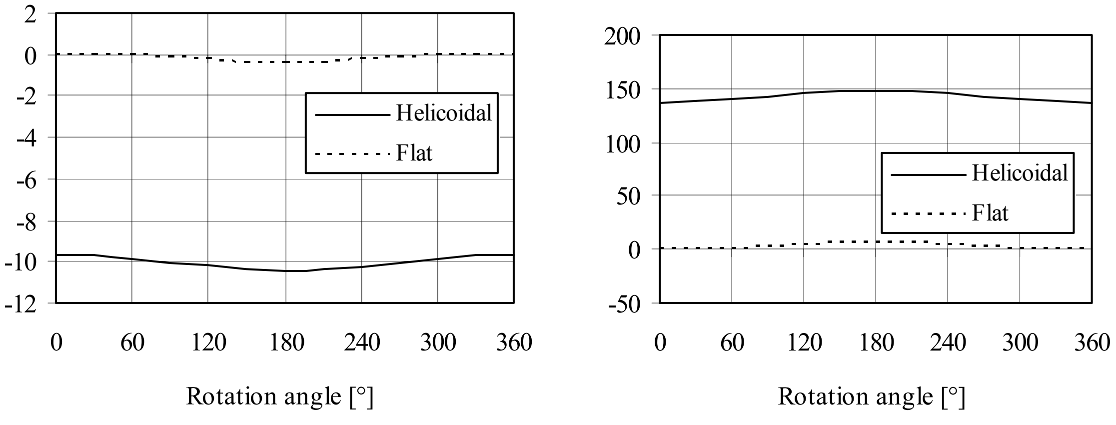


Figure 3 vertical displacement [μm] (left) and rotation around horizontal axis [μrad] (right) due to torsion only: comparison between helicoidal and flat planar cracks.

It can be seen that the helicoidal crack generates a higher flexibility with respect to the flat crack: all deflections, except the torsional rotation, are higher with the same load. This result could be expected as the positive torsion forces the crack to open, but the stiffer torsional behaviour is surprising.

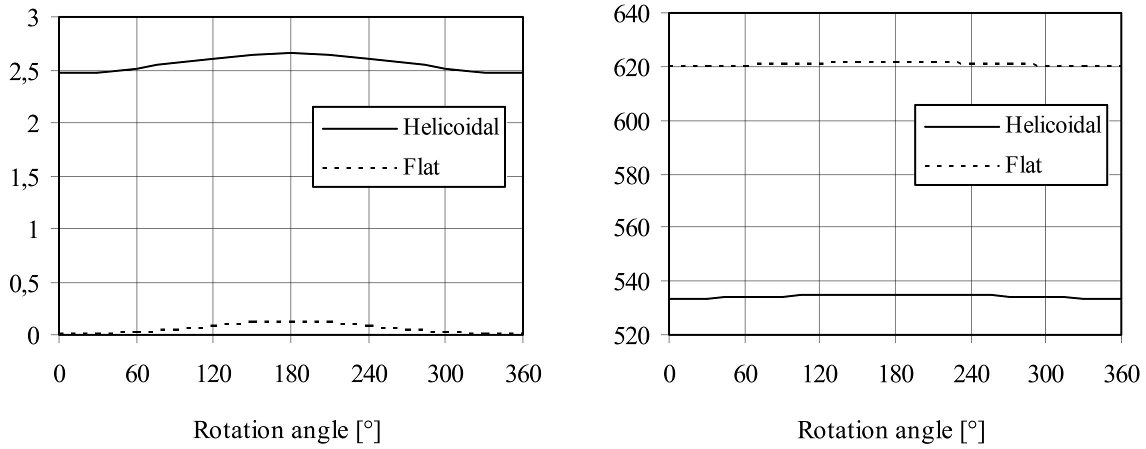


Figure 4 axial displacement [μm] (left) and torsion rotation [μrad] (right). Helicoidal crack compared to flat crack loaded by torsion only.

Since the behaviour shows a strong sensitivity to torsion, an analysis has been made with constant bending load (as it is in the real machine) and increasing torsion loads (as it occurs during the start up of the group), also in order to check how far the overall behaviour can be considered linear or quasi-linear. Bending load has been assumed equal to 600 Nm and torsion is respectively 0, 200, 400, 600, 1200 Nm for loading condition LC1, LC2, LC3, LC4 and LC7. Fig. 5 shows the results in deflections along vertical and torsional directions. The overall behaviour can be considered quite linear: the deviations from 0 torsion load behaviour are roughly proportional to the torsion load.

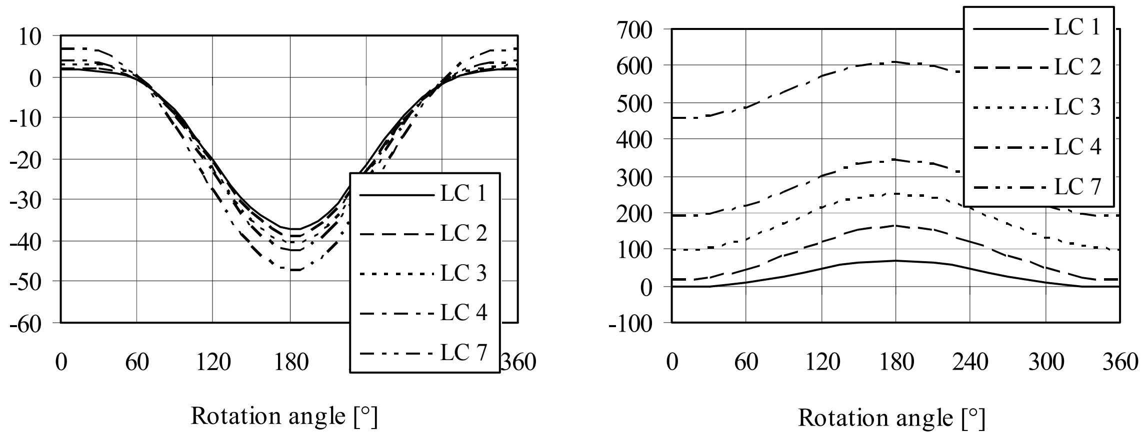
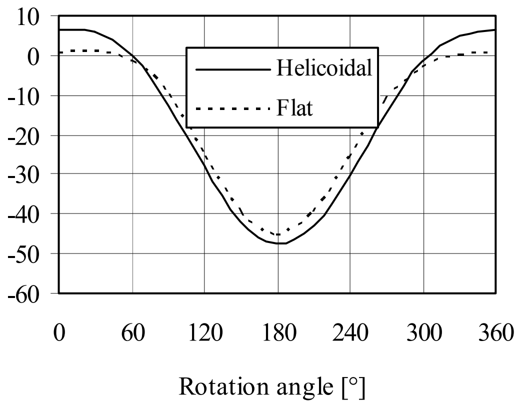


Figure 5 Left: axial displacement [μm] Right: torsion rotation [μrad]. Helicoidal crack loaded by constant bending load and increasing torsion loads.

Finally the behaviour in 3 different loading conditions have been compared to the behaviour of the flat crack: full load condition, no torsion load condition (when electrical load is removed from generator) and negative torsion load (Mt = -200 Nm) condition (during coast down breaking due to condenser vacuum rupture). Fig. 6 shows the differences in deflections according to the vertical and torsional degrees of freedom between the helicoidal crack and the transverse crack in full load condition. For this kind of crack at full load the differences between helicoidal and flat crack are so small that they could be neglected. Fig. 7 shows the differences in 0 torsion load conditions between the helicoidal and the transverse crack. In the no torsion load condition only small differences are found in all degrees of freedom, where the helicoidal crack is more stiff, except for the torsion degree of freedom where the bending load excites more strongly the torsional deflection. Fig. 8 shows the differences in deflections between helicoidal and transverse cracks in negative torsion load condition. In this case the helicoidal crack has a still stiffer behaviour with respect to the transverse crack, because the negative torsion tends to hold the crack more closed.



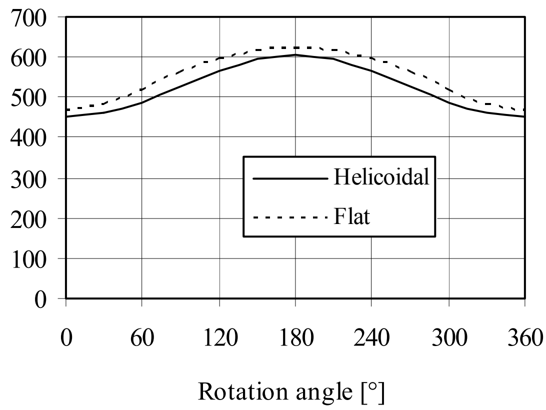


Figure 6 Vertical displacement [μm] (left) and torsional rotation [μrad] (right): comparison between helicoidal and flat crack in full load condition

As can be seen with negative torsion, condition which could occur during a run down transient, the helicoidal crack behaves in a stiffer way with respect to the flat crack: therefore the deflections and also the excited vibrations in the rotating shaft due to coupling effects will be much smaller with respect to the flat crack.

Summarizing the results it seems that at full load the differences between helicoidal and flat crack are so small that they could be neglected.

When torsion load is removed then higher differences arise but mainly for the torsional degree of freedom, which is excited by the bending load by means of a coupling effect.

When torsion load becomes negative, then the behaviour is stiffer and the torsion excitation disappears.

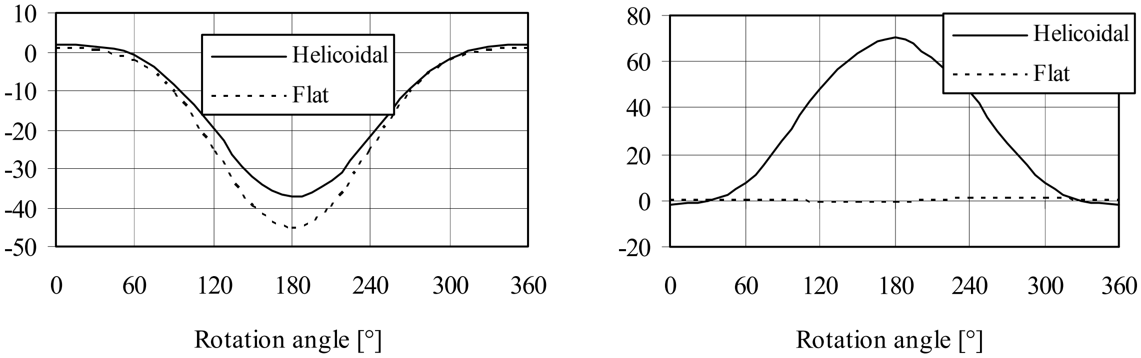


Figure 7 Vertical displacement [μm] left and torsional rotation [μrad] right: comparison between helicoidal and flat crack in no torsion load condition

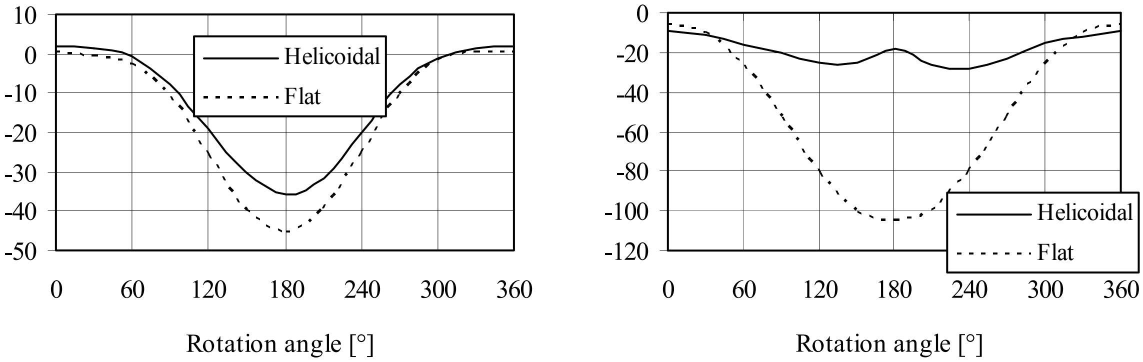


Figure 8 Vertical displacement [μm] left and torsional rotation [μrad] right: comparison between helicoidal and flat crack in negative torsion load condition

If full load condition is compared to only bending load, some unexpected effects can be noted. In the vertical displacement, close to 0° or 360° of rotation of the load when the crack is hold closed by bending moment, the expected value is 0 as for the flat closed crack. Instead a small positive value has been found, with respect to the un-cracked shaft. A similar behaviour can be noted in the rotation around the horizontal axis and in the axial displacement (not shown for brevity). Despite the fact that the crack is closed, the beam with the helicoidal crack is more flexible with respect to the un-cracked beam. This can be explained by analysing accurately the relative displacements of the crack lips: the high torque generates a relative torsion displacement of the crack lips, which are helicoidal; due to this torsion the lip surfaces are not anymore corresponding each other, a small clearance is available between the lips, and the bending moment overcomes the clearance and brings the lips together in its new position. This clearance is responsible for allowing positive displacements.

CONCLUSIONS

A 3D model for helicoidal crack has been shown and the obtained results in terms of deflections according to several degrees of freedom have been compared with 3D transverse crack model results, showing generally only small differences between the two cases, in different loading conditions. Torsion loads however emphasize differences in behaviour.

The presence of torsion increases the deflections, when (positive) torsion opens the crack and lowers consequently the stiffness, the opposite happens when (negative) torsion closes the crack and increases its stiffness. When torsion is absent then the torsional deflection is rather strongly excited by the bending, much more with respect to the flat transverse crack.

All these results hold for helicoidal cracks with a small slope of the helicoidal crack surface only: slant cracks with slopes of the helicoidal surfaces up to 45° need further analyses.

These statical results allow to forecast also the dynamical behaviour of rotating shafts affected by helicoidal cracks, at full load and when the torsion load is removed. Coupling effects between bending and torsion, which depend on the amount and direction of the applied torque, are emphasized by the helicoidal crack and constitute the main difference with respect to a planar transverse crack. Therefore torsional vibrations are easily excited by the helicoidal crack due to the coupling effect with bending loads when no torsion load is applied: torsional resonances could be excited during run down transients of turbogroups affected by helicoidal cracks. This could constitute an additional symptom useful for diagnostic purposes.

Axial deflections and consequently also axial vibration excitation seem to be rather small in general and still smaller for helicoidal cracks.

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