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Investigation of crack propagation path in tube gears

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Abstract

In this paper, the crack propagation behaviour in tube gears has been investigated. This kind of gear find application in aerospace and in particular in helicopter drivelines. For this reason, an accurate design against catastrophic failure due to particular crack propagation paths, has to be performed. In this work, the effect of tube length and rim thickness and also speed on crack propagation path has been analysed by means of extended finite elements models. In particular, to better understand the effect of speed, the changes in stress intensity factors K_I and K_{II} have been considered. Particular crack propagation shapes (wave propagation) have been found in some cases where the length ratio is particularly high.

Keywords: fracture mechanics; crack path; crack propagation; gears; XFEM.

1. Introduction

Lightweight gears are used in applications where weight reduction is a key factor, such as in aerospace industry. They are characterized by quite thin geometries and are realised in different shapes, according to the application requirements. These kinds of gear is geometrically characterized by thin rim thickness, Lewicki et al. (1997), and, if it is present, by a thin web thickness, Curà et al. (2015). Considering planetary gearboxes, in particular for helicopter applications, the solution to reduce weight consist in realizing satellites whose internal diameter is used as internal bearing race, Curà et al. (2016), and the sun as a part of the shaft. In this work, we focus on sun gear.

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Sun gear for helicopter applications has particular shape that may be described as “tube shape gear” (see Figure 1). This kind of lightweight gears may be geometrically characterized by rim thickness and tube length.

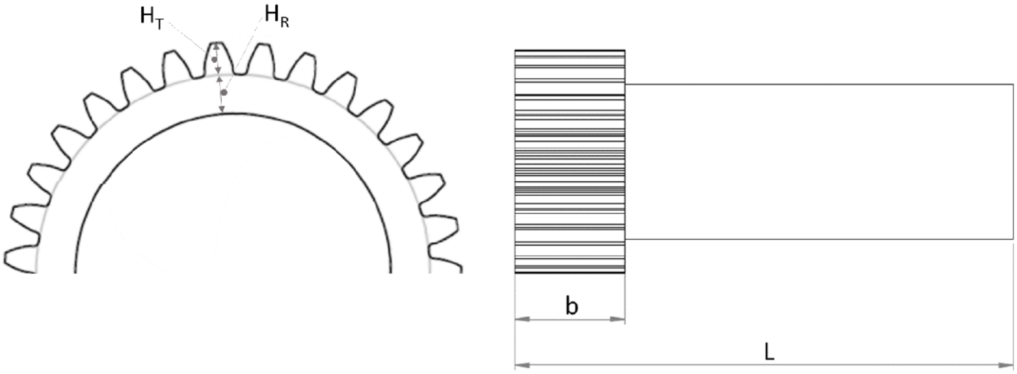

Fig. 1. Tube shaped gear.

As other aerospace gears, also tube shaped gear has to be designed with a failsafe approach, in order to avoid catastrophic failures, Lewicki (2011).

In the literature, many works may be found investigating the crack path behaviour in thin rim gear. Glodez et al. (1998) experimentally investigated the effects of different load distributions, while Pehan et al. (1998) made a numerical investigation about the effect of non-uniform load distributions and non-uniformly crack growth along the tooth width.

Other authors focused on life estimation, as Flasker et al. (1998), that evaluated the effect of different loading conditions on the residual life of wheels with a crack along the tooth root. Podrug et al. (2008) considered the effect of moving gear tooth load on the gear service life.

Rad et al. (2014) calculated the fatigue life of a helical gear by means of the extended finite element method (XFEM); Kramberger et al. (2004) investigated the effect of rim thickness on bending fatigue life of a thin-rimmed spur gear by finite element and boundary element methods. Lalonde et al. (2011) studied the effect of teeth number, speed, rim thickness, initial crack length, initial crack orientation and relative fillet position on the crack path propagation by means of boundary element simulations. One of the main parameters affecting crack path is the initial crack position, Curà et al. (2014).

Initial crack position may be influenced by both wheel rotation speed and external bending load, Curà et al. (2015). Crack path in thin rim gear may also be influenced by centrifugal loads as shown in some works as the Lewicki (2001) one, where experiments and 2D finite element results are shown. Li, in his two works, Li (2008), Li (2013), investigated, by means of FE models, the effects of centrifugal load on bending, contact strength and deformations of a high speed thin-rimmed spur gear, and Curà et al. (2016) investigated the effect of high speed on crack path by extended finite elements models.

All these works consider the effect of rim thickness, web thickness, load conditions, etc, but the literature is lacking about the crack path behavior of tube shape gears. In this kind of gear, the effect of tube length has to be taken into account.

To this aim a geometrical parameter named length ratio has been introduced (it consists in the ratio between tube length and face width).

In this work, the crack propagation path of tube shape gears has been investigated, considering the effect of both rim thickness and tube length and the effect of speed. The investigation has been carried out by means of extended finite elements models (XFEM).

Nomenclature

B	face width;
F	bending force;
K_I	mode I stress intensity factor;
K_{II}	mode II stress intensity factor;
H_R	rim thickness;
H_T	tooth thickness;
L	tube length;
m_b	backup ratio;
m_w	web ratio;
W	web thickness.

2. Numerical models

From different works available in the literature, three different behaviors have been identified (safe failure, uncertainty zone, catastrophic failure), Lewicki (2001), related to different backup ratios ranges. In the present work, tube shaped gears with different rim thicknesses (belonging to all the three above quoted backup ratios ranges) have been considered, in order to investigate if these kinds of gears have the same behavior of "classical" thin rim gears. Then the effect of length has been considered in order to investigate its influence on crack path direction. The main characteristics of tube gears considered in this work are: 31 teeth, modulus = 3mm, face width = 51mm, pressure angle = 20°.

Table 1. Gears parameters (B = bending load; S = centrifugal load.

Test Case	Backup ratio	Lengh ratio	Load
1	0.2	1.1	B
2	0.2	1.1	B+S
3	0.2	2	B
4	0.2	2	B+S
5	0.2	4	B
6	0.2	4	B+S
7	0.2	6	B
8	0.2	6	B+S
9	0.4	1.1	B
10	0.4	1.1	B+S
11	0.4	2	B
12	0.4	2	B+S
13	0.4	4	B
14	0.4	4	B+S
15	0.4	6	B
16	0.4	6	B+S
17	0.6	1.1	B
18	0.6	1.1	B+S
19	0.6	2	B
20	0.6	2	B+S
21	0.6	4	B
22	0.6	4	B+S
23	0.6	6	B
24	0.6	6	B+S

Three different rim thickness values have been considered with four different tube lengths. In addition, the effect of speed has been investigates, running, for each geometry, simulations without and with centrifugal load, consisting in rotating speed of 10000rpm. Table 1 resumes all test cases analyzed in this work.

Models consist in 3D extended finite elements (XFEM) created by Simulia Abaqus. The crack has been initiated at the point where the maximum equivalent stress is achieved. This point has been previously obtained by means of static FE analysis. The initial crack has ellipse shape with 0.25 mm length for the mayor axis and 0.1mm length for the minor one. The initial crack orientation is perpendicular to the tooth fillet tangent. The load consists in a force distributed along the face width, applied at the pitch diameter (see Figure 2). In some cases, a centrifugal load has also been applied, according to the test cases resumed in Table 1. The wheel has been blocked at the free end of the tube, as shown in Figure 2.

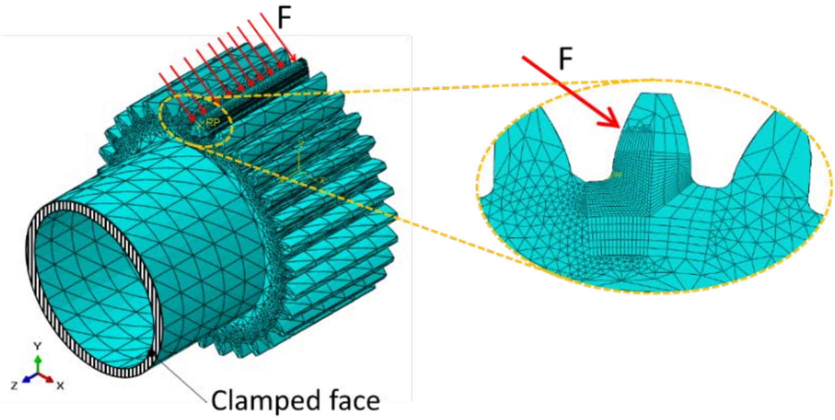

Fig. 2. FE model.

The crack propagation has been calculate by the Virtual Crack Closure Technique (VCCT). This method considers that the released energy during the crack propagation is equal to the energy necessary to close the crack, Collini et al. (2011).

3. Results and discussion

It is interesting to compare the crack path behavior of tube shaped gears against the behavior of classical thin rim gears whose been investigated in many works available in the literature. First of all, it is important to highlight that tube shaped gears, compared to standard gears, are subjected to both bending and torsional stresses. Because of the boundary conditions, the bending stress is higher as the length ratio increases.

According to the literature considering classical thin rim gears, one of the main parameters influencing the crack propagation path is the backup ratio, Lewicki et al. (1997).

In particular, if the backup ratio is higher than one, the crack propagates through the tooth (safe failure), if the backup ratio is less than 0.5, the crack propagates through the rim (catastrophic failure) and, if the backup ratio is between 0.5 and 1, the crack path depends from other parameters (i.e. crack initiation position, speed, etc).

Considering tube shaped gears, Figure 3 shows some examples of the obtained results considering gears with backup ratio respectively of m_b= 0.4 (Figure 3a) and m_b= 0.6 (Figure 4b), with different length ratios. From these images, it is possible to observe that the tube length (length ratio) seems not to influence the crack path direction in the frontal view, but (as will be shown in the next section), it may influence the crack path shape on the face width direction.

Table 2. crack propagation paths in tube shaped gears: T = propagation through the tooth, R = propagation through the rim.(B = bending load S = speed load).

Backup ratio m_b	Length Ratio L_R							
	1.1		2		4		6	
0.2	T	R	T	R	T	R	T	R
0.4	T	T	T	T	T	T	T	T
0.6	T	T	T	T	T	T	T	T
1	T	T	T	T	T	T	T	T
Load type	**B**	**B+S**	**B**	**B+S**	**B**	**B+S**	**B**	**B+S**

Table 2 resumes all crack propagation results obtained in this work. In particular, the letter T means that the crack propagated through the tooth, while the letter R means a propagation though the rim. Table 2 also shows the effect of the centrifugal load, in particular the letter B means that the simulation ran with only bending load, while B+S means that the simulation involved both bending and centrifugal loads.

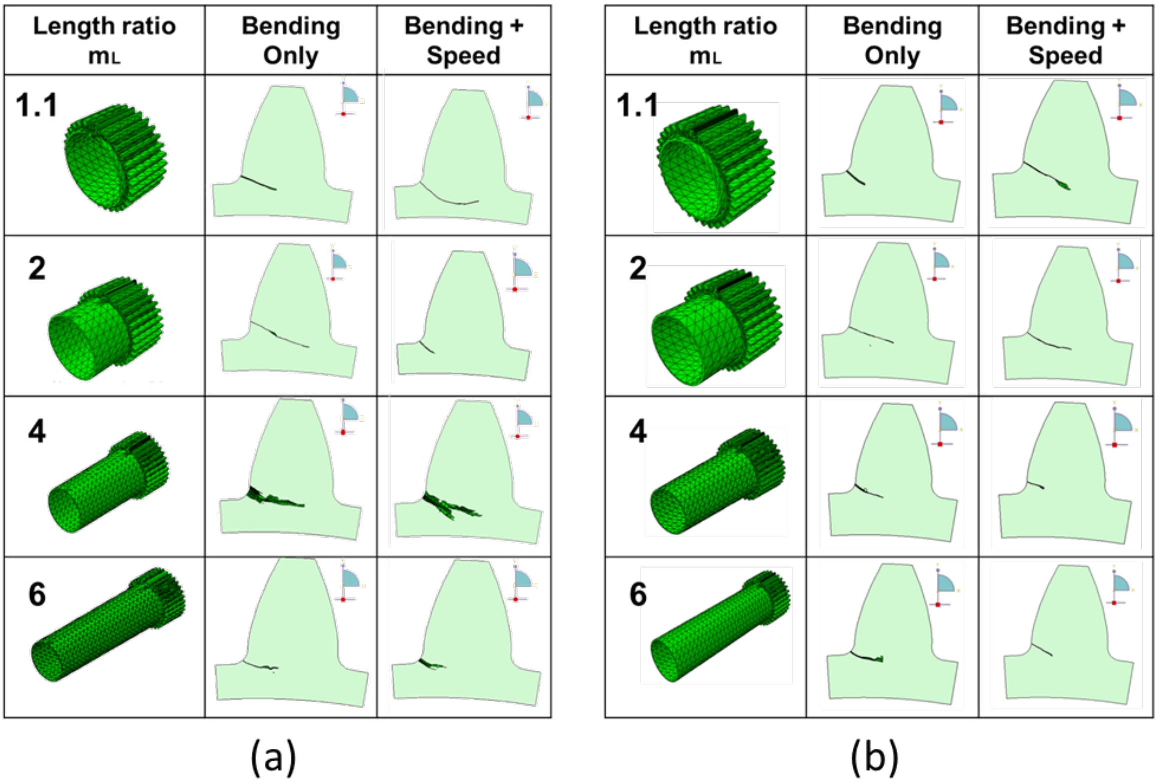

Fig. 3. Results for backup ratio = 0.4 (a) and for backup ratio = 0.6 (b)

These results are very interesting because show that in tube gears the crack seems always to propagate through the tooth in case of negligible centrifugal load, independently from the value of the backup ratio.

This behavior is very different respect to classical thin rim gears, where, as explained before, the backup ratio defines the crack path. It is also interesting to highlight that the centrifugal load affects the crack path only in case of very thin rim (m_b = 0.2), while in classical thin rim gears its effect is very important also for backup ratio up to 1, Curà et al. (2015). Anyway, in most of cases the centrifugal load acts on the crack path shifting the crack propagation in a direction more close to the rim.

3.1. Effect of centrifugal load on stress intensity factors

To better understand how the crack path direction may change when the centrifugal load is applied, the values of stress intensity factors K_I and K_{II} have been evaluated for two tests where crack propagates respectively through the rim (Test Cases 1, Figure 4(a)) and through the tooth (Test Cases 2, Figure 4(b)). Stress intensity factors have been calculated in different simulation steps.

From Figure 4 it is possible to observe that, when the crack propagates through the rim, the stress intensity factor K_I always increases while K_{II} always decreases. On the other hand, when the crack propagates through the tooth (Figure 4(b)), K_I has again an increasing trend, while K_{II} at the beginning of the propagation tends to decreased and then it change its values and increases up to the end of the propagation.

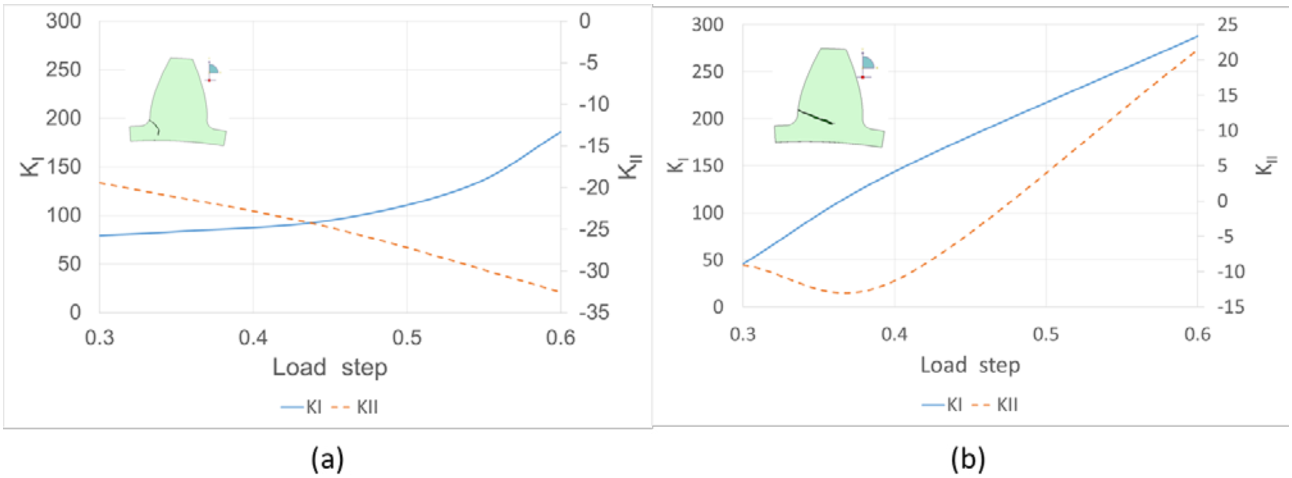

Fig. 4. K_I and K_{II} trends for a crack propagated through the rim: (a) Test Case 1: bending + centrifugal load; (b) Test Case 2: only bending load

3.2. Effect of length ratio (wave shaped propagation)

Results show that long tube gear (length ratio >2) have a particular crack propagation path (see Figure 5).

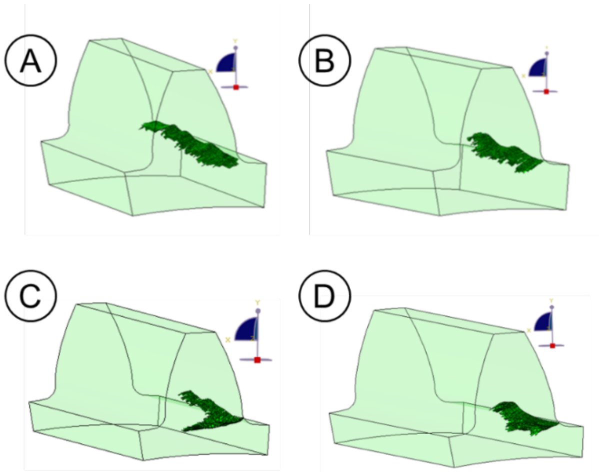

Fig. 5. Wave shaped crack paths for test case 22 (A), test case 24 (B), test case 13 (C) and test case 15 (D).

As a matter of fact, in these gears the crack propagates in the face width direction, with sinusoidal shape.

In these cases the crack first propagates in the tooth (or rim) direction and then the propagation continues in the face width direction. Although the most number of investigation on crack propagation are related to straight cracks, in the literature it is possible to find only few works about sinusoidal cracks. In particular, this kind of propagation has already been observed in the literature, a in glass plate subjected to thermal stress and in polyethylene tubes with high pressure gas, Fujimoto (2009).

The mechanism of sinusoidal crack path is not completely understood, but it seems to be related to the stress intensity factors ratio ($K_{II}/K_{I,}$) Lu et al. (1989). In particular if the $K_{II}/K_I > 0$ the crack turns by side and if $K_{II}/K_I < 0$ the crack goes through the opposite side, Fujimoto (2009).

4. Conclusions

In the present paper the crack path behavior of tube gears has been investigated in order to fill the lack existing in the scientific literature about this subject.

To this aim, the effect of the tube length has been taken into account and some new design guidelines have been established for tube gears, able to prevent catastrophic failure modes.

In addition to the classical parameters (back up ratio and web ratio), a new geometrical parameter named length ratio has been introduced, consisting in the ratio between tube length and face width.

Three effects have been considered: two related to the gears geometry (rim thickness and tube length) and one related to the load condition (bending with or without the effect of the centrifugal load).

3D XFEM technique has been successfully used to analyze tube gears for as concerns crack propagation paths. Twenty four test cases have been run, referring to twelve different gears geometries (three back up ratio and four length ratio values) and two loading conditions (bending and bending with centrifugal loads). As already done in previous papers, the initial crack has been positioned at the point in the tooth root fillet where the maximum equivalent stress (Von Mises) has been achieved.

Then, by reasoning strictly from the geometrical point of view, the tube length (length ratio) seems not to influence the crack path direction in the frontal view, but it may influence the crack path shape in the face width direction. In particular, long tube gears showed a crack propagation path with sinusoidal shape in the face width direction.

For as concerns the frontal view, the behavior of tube gears is totally different respect to classical thin rim gears where the backup ratio substantially defines the crack path. As a matter of fact, the crack seems always to propagate through the tooth in case of negligible centrifugal load, independently from the value of the backup ratio.

If the centrifugal load is considered in simulations, in most cases this condition causes a shift of the crack path in a direction more close to the rim.

Finally, to better investigate this phenomenon, in two cases with the same geometry, but respectively without and with centrifugal load, the values of the stress intensity factors K_I and K_{II} have been calculated at different simulations steps. Stress intensity factors values (K_I and K_{II}) showed a trend that seems to emphasize a different behaviour related to propagations respectively through the rim (the ratio between K_I and K_{II} has always the same sign) or through the tooth (the ratio between K_I and K_{II} changes in sign).

Values of the ratio between stress intensity factors (K_I and K_{II}) seemed also related to the phenomenon of sinusoidal crack paths, but this mechanism of propagation needs to be further investigated.

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