Focussed on: Fracture and Structural Integrity related Issues

Investigation about crack propagation paths in thin rim gears

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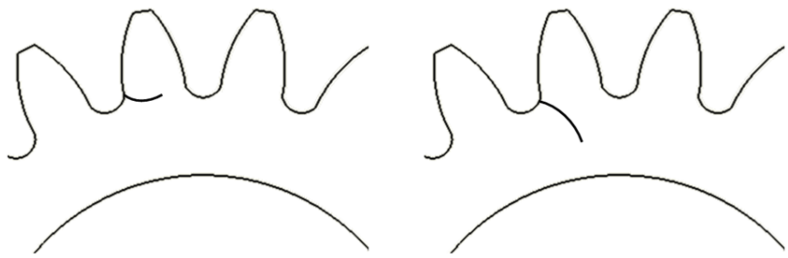
ABSTRACT. Crack propagation in gears is a problem related not only to the life of the components, but also to the concept of failsafe design. Fail safe design means to design a component in order that, if a failure occurs, this may cause a "safe failure". This aspect is very important above all in aerospace industry. As a matter of fact, in aerospace application, the need of reducing weight brings to produce gears with very thick rim and web. Considering thin rim gears, when a crack is nucleated near the tooth root, it may propagate through the tooth (causing the loss of the entire tooth or a portion of it) or the propagation may follow a path across the wheel diameter (causing the projection of big parts of the gear that may break the gearbox and may cause serious damage to the aircraft). The first failure mode is define as "failsafe failure" and the second one as "catastrophic failure" and of course has to be avoided.
Designers need to have robust design criteria in order to predict crack propagation paths and to avoid catastrophic failures. In literature, few works are present concerning this topic, in particular related to the effect of geometrical parameters that may affect the crack propagation.
In this work a numerical analysis about crack propagation in gears with respect to the backup ratio (ratio between tooth height and rim thickness), initial crack position and shape has been done by means of the Extended FEM (XFEM) technique, realizing 3D models. XFEM 3D is a relatively new technique consisting in enriching traditional finite elements with more complex shape functions; in this way it is possible to propagate crack also between mesh nodes and to have mesh independent results.
Aim of this paper is to highlight the crack propagation path in order to give to designers an high confident design criterion, related to the gear geometry.
In particular, the effect of both rim thickness and orientation of the initial crack have been considered in order to enrich the literature knowledge. Numerical results obtained in this work have been compared with those found in the literature, showing a very good correlation.

KEYWORDS. Gear; Crack; Propagation; Rim; XFEM.

INTRODUCTION

In some industrial field, such as in aerospace industry, it is necessary to design components not only to avoid failures, but also to control the damaging behavior in order to avoid catastrophic failure modes. This way to design is also known as "fail safe design" [1]. As an example, gears used for aerospace application have to be as light as possible and so these components present thin thickness for both rim and web.

As a matter of fact, if a crack occurs in thin rim gears near the tooth root, it may propagate along the tooth thickness direction by cutting the entire tooth, or the crack may propagate along the radial direction by destroying the whole gear, see Fig. 1 (respectively **a** and **b**).



a) b)

Figure 1: Possible failure modes in a thin rim gear: a) safe fail, b) catastrophic fail.

The first failure mode is the desired one (Fig. 1a), as it may allow the airplane to land safely, while the second one may bring to the projection of big parts of the gear with consequent catastrophic damages to the whole transmission.
This work is focused on the analysis of crack propagation path on thin rim gears and, in particular, the effect of both rim thickness and initial crack orientations has been investigated.
Some researchers studied the effects of the rim thickness on the stress entity, but only a few have carried out an analysis of fatigue crack growth.
Among works available in literature about gears crack propagation paths, the most relevant are those carried on by Lewicki et al. [1 - 5] where both experimental and numerical investigations have been presented. These papers consider gears without web and the experimental investigation has been focused on the effect of rim thickness [1]; the corresponding numerical investigation (performed with 2D FEM models) was referred to the effect of some geometrical parameters, to the initial crack location ant to the load application point.
Experimental tests were carried out also by Glodez et al. [6], but this research was focused on the effects of different load distributions along the tooth width on the growth of fatigue cracks.
Kramberger et al. [7] proposed a model to predict the bending fatigue life of cylindrical gears with thin rim, including the two stages of initiation and propagation of cracks. The study of the propagation phase involved the determination of the trajectory of the crack propagation, which could be through the root of the tooth or the crown of the wheel and the useful life remaining until the final collapse.
Flasker et al. [8] investigated the effect of the contact area on the crack propagation direction and evaluated the residual life of the wheel with a crack along the tooth root for different loading conditions, both experimentally and numerically.
Kato et al. [9] developed a method to simulate the growth of a fatigue crack in carburized tooth by considering the effect of residual stresses, but by neglecting the crack initiation period.
The effect of the crack closure on the propagation was investigated by Ural et al. [10] and Guagliano et al. [11]. The results of their analysis showed that the effect of the crack closure could be significant when the applied load is lower and the crack propagation phase represents a significant portion of the wheel life. Studies in three dimensions are required in case of not uniform load distributions or when the crack does not growth uniformly along the tooth width. One example is the analysis carried out by Pehan et al. [12].
Other simulations about cracks growth in three dimensions were carried out by Lewicki, [3] which study allowed to obtain the following conclusions: initial cracks in the connection to the bottom of the tooth produce higher stress intensity factors (and thus the crack growth rate increases) than those in the tooth root area. Kramberger at al. [13] investigated the effect of different web positions on the crack propagation path in thin rim gears.
In this work a numerical analysis about crack propagation in thin rim gears has been carried on; in particular the effect of some geometrical parameters, the initial crack position and shape has been investigated. Numerical models have been developed by means of the Extended FEM (XFEM) technique, realizing 3D models. XFEM 3D is a relatively new technique consisting in enriching traditional finite element with more complex shape functions; in this way it is possible to propagate cracks also between mesh nodes and to have mesh independent results [14].
Aim of this work is to predict the crack propagation path orientation, by knowing geometrical gear parameters and initial crack position, in order to avoid catastrophic failures and to give to designers a high confident design criterion. In particular, the effect of rim thickness and the orientation of the initial crack have been considered in order to enrich the literature knowledge. Numerical results obtained in this work have been compared with results found in the literature [1].

XFEM MODELS

In this work the crack propagation path has been investigated by means of extended finite element (XFEM) models. Fracture mechanics isnot properly implemented in the classical FEM models. As a matter of fact crack propagation is defined by geometric entities which are treated as the new endpoints of the structure. It follows that the mesh must be consistent with the crack position.

In order to consider the singular stress field near the crack tip, it is necessary to provide an area with a particular mesh. This start point involves a complication in the mesh management, especially when studying the crack growth, as this requires a redefinition of both geometry and mesh at each calculation step. These limitations may be overcome by the technique eXtended Finite Element Method (XFEM) [14].

With this technique, the finite element mesh is enriched by incorporating local functions to represent the jump in the displacements along the crack and near the tip. The mesh does not have to match the position of the crack and it is no longer necessary to define an area of the crack in the mesh, as the singular stress field is included in the problem. The study of the crack propagation can be done without proceeding with a new phase of re-meshing, but simply making sure that the mesh is fine enough in the area of the crack tip in order to obtain accurate results.

This investigation has been carried on by using a thin rim gear made of steel, which main characteristics are resumed in Tab. 1.

Modulus [mm]	7.4
Teeth number	28
Pitch Diameter [mm]	206.4
Pressure Angle [°]	20
Face width [mm]	8

Table 1: Gear parameters.

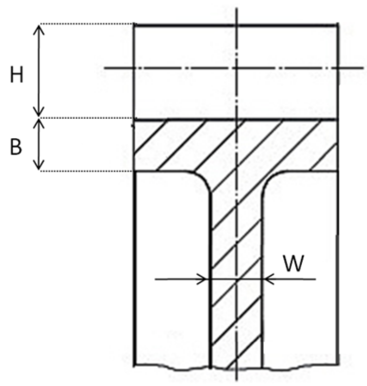


Figure 2: Gear geometric parameters: tooth height (H), rime thickness (B), web thickness (W).

m_B	W [mm]
Full Gear	8
1	4
0.5	4
0.4	4
0.3	4

Table 2: Gear geometric parameters.

Different models have been created by varying rim thickness B, crack position and crack orientation.

From the geometrical point of view, five rim thickness values have been considered, referred to the tooth height, as generally reported in literature. This geometrical parameter is known as backup ratio m_B and it is indicated as the ratio between rim thickness B and tooth height H: $m_B = B/H$.

Two different web thickness values have been also considered. The above quoted geometrical parameters are resumed in Tab. 2.

Cracks have been positioned on five points equally distributed along the tooth root fillet, starting from the involute up to the middle of the tooth vane (Fig. 3). So for each gear geometry (see Tab. 2), five cases have been run.

The effect of the initial crack orientation has been taken into account, in the full gear, by considering three different conditions: the first one with the crack perpendicular to the tangent of the tooth root fillet, second and third ones respectively with 45° clockwise and counterclockwise directions (Fig. 4).

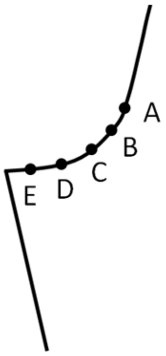


Figure 3: Initial crack position points.

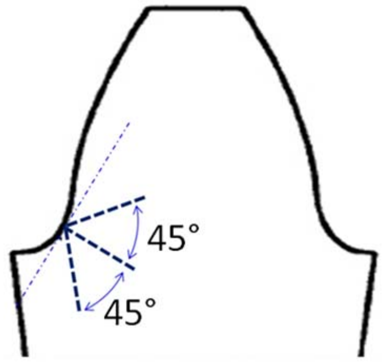


Figure 4: Initial crack orientation in the tooth root fillet region.

Totally 40 (20 for the full gear and 20 for the thin rim gear) numerical models have been created by means of Smacef v15 software.

Firstly, gears have been meshed by traditional 3D finite element, then the region near the crack has been enriched with XFEM elements (Fig. 5); XFEM region has to be as big as the crack may be included during the propagation, but not too big in order to avoid long calculation time. The dimensions of the element in the XFEM region is 0.4mm.

An elliptical crack has been inserted at one extremity of the tooth width.

Gears have been loaded by a distributed force applied at the pitch diameter along the tooth width; the gear hub has been considered as clamped.

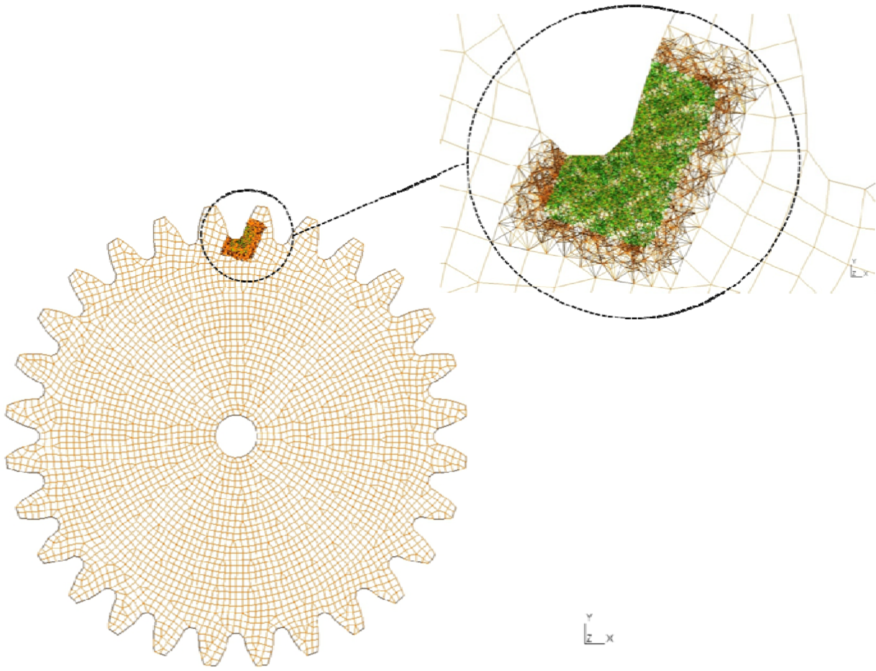


Figure 5: Mesh of the gear model with XFEM region.

RESULTS AND DISCUSSION

Results show that the crack propagation path is generally influenced by both rim thickness and initial crack position, while initial crack orientation doesn't seem to affect crack propagation.

Tab. 3 resumes the main results concerning the effect of rim thickness and initial crack positions obtained from the simulations, where the letter *S* stands for the propagation direction along the tooth thickness (safe failure) and *C* stands for the propagation in radial direction (catastrophic failure).

	Initial crack position point				
Backup ratio	A	B	C	D	E
Full Gear	*S*	*S*	*S*	*S*	*S*
1	*S*	*S*	*S*	*C*	*C*
0.5	*S*	*C*	*C*	*C*	*C*
0.4	*C*	*C*	*C*	*C*	*C*
0.3	*C*	*C*	*C*	*C*	*C*

Table 3: Crack propagation direction for different backup ratios and initial crack position (*S* = propagation along tooth thickness, *C* = propagation in radial direction).

Considering the full gear, results show that the crack path brings always, independently form the initial crack position, to the tooth removal (fail safe), as shown in Fig. 6.
On the other hand in thin rim gears the initial crack position seems to affect the crack path and, in particular, if the crack nucleates near the bottom of the tooth fillet (points D and E, Fig. 3), then it follows a path in radial direction bringing to a catastrophic failure.

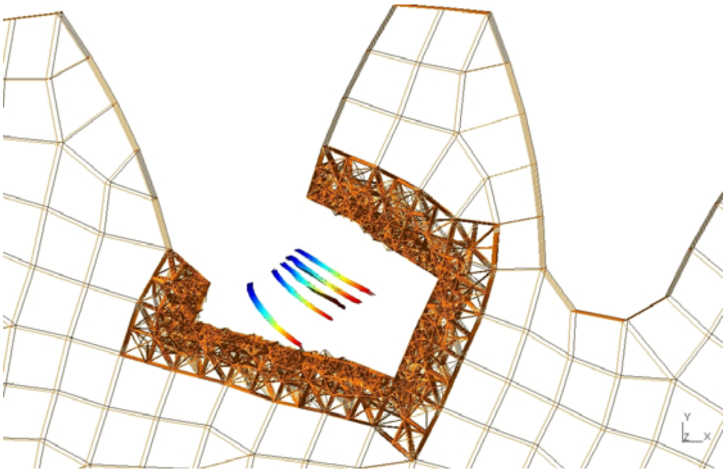


Figure 6: Crack paths for different initial crack positions for the full gear.

As an example Fig. 7 and 8 show the crack paths for backup ratio m_B respectively 1 and 0.5.

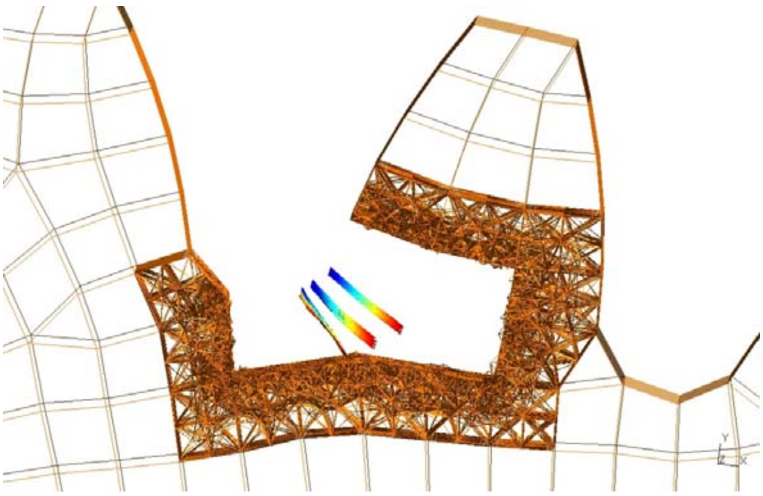


Figure 7: Crack paths for different initial crack positions for thin rim gear (m_B = 1).

It may be observed that the initial crack orientation, in all models, doesn't affect the crack propagation path independently form the initial crack position.
As an example Fig. 9 shows the results obtained for the gear with $m_B = 1$ and considering the initial point A; it is possible to observe that after the initial propagation phase the cracks follow the same direction.
For sake of clarity, in Fig. 7 only cracks propagating from points A, C, D are shown. In Fig. 8 cracks from points A and D are reported.

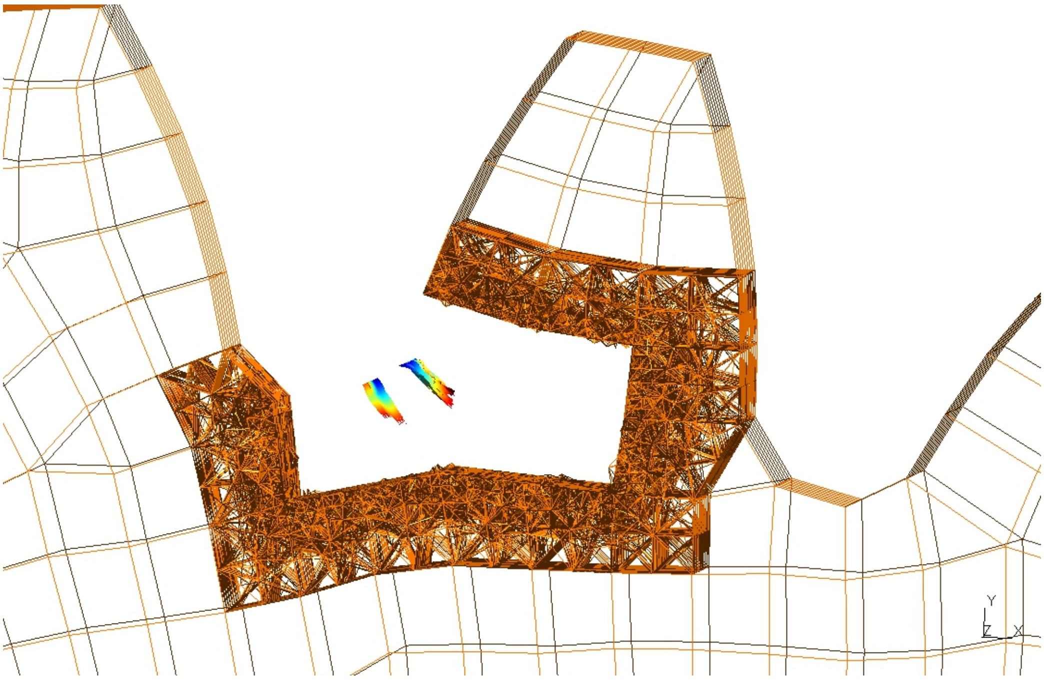


Figure 8: Crack paths for different initial crack positions for thin rim gear ($m_B = 0.5$).

Finally, considering the effect of the rim thickness, results show that for the full gear, as written above, the crack propagates always in the tooth direction independently form the initial crack position but, if backup ratios $0.3<m_B\leq 1$ are considered, the crack growth direction depends on the initial crack position and for $m_B<0.3$ the crack propagates always in the radial direction, potentially bringing the gear to a catastrophic failure (Fig. 10).

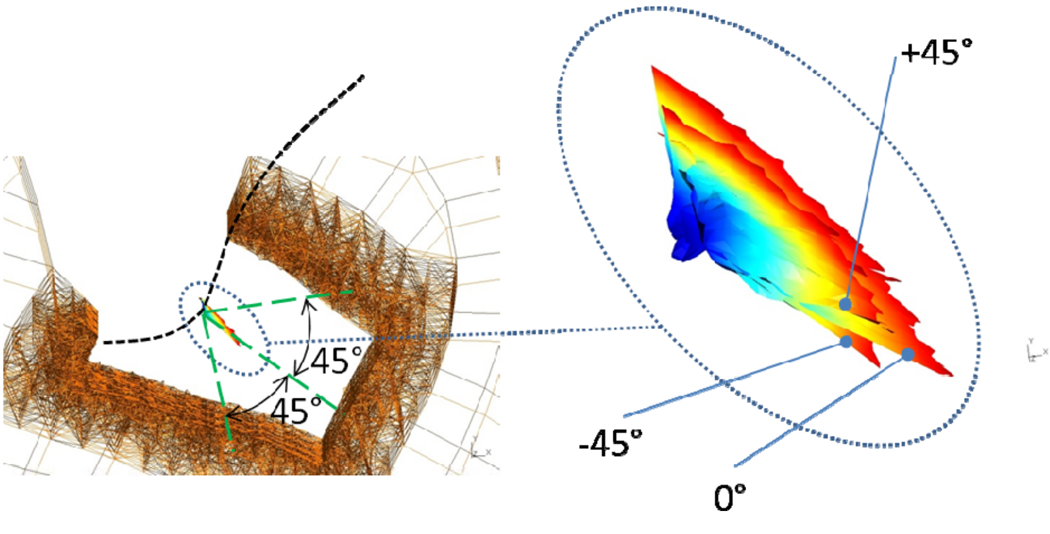


Figure 9: Effect of initial crack orientation (gear with $m_B = 1$, nucleation point A).

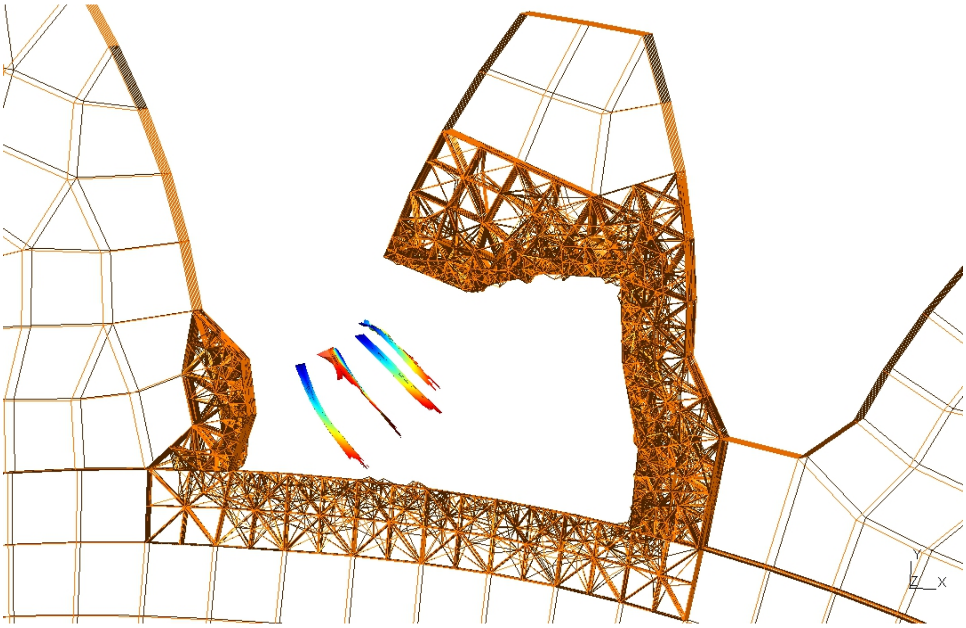


Figure 10: Crack paths for different initial crack positions for thin rim gear (m_B = 0.3).

CONCLUSIONS

In this work a numerical investigation about crack propagation path in thin rim gears has been done. In particular this work is focused on the analysis of the two different failure modes that a crack may cause on a gear: safe failure, if the crack growth through the tooth, and catastrophic, if the crack propagates in the radial direction.

Numerical models have been meshed by using XFEM technique.

The effect of rim thickness, initial crack position and initial crack orientation have been investigated. In order to better represent the value of the rim thickness respect to the gear geometry, according to the literature, the ratio between rim thickness and tooth height (backup ratio) has been adopted.

Results shows that the crack propagation path depends on both backup ratio and initial crack position, while the initial crack orientation seems not to affect crack path. In particular if the full gear is considered crack paths seems not to be influenced by the initial crack position and cracks growth through the tooth; on the other hand, thin rim gears (gears with backup ratio ≤ 1) the initial crack position may change the crack path direction.

If the rim thickness reduces and consequently the backup ratio decreases up to 0.4, again the crack path seems not to be influenced by the initial crack positions, but this time the growing path is in radial direction through the wheel.

This work represents a first step of an ongoing research that will take into account other geometric parameters and others influencing factors such as rotational speed.

So the main goal of this activity is to give to designers consistent information about gears geometry in order to avoid catastrophic failures possibilities.

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