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Numerical analysis of fracture mechanisms and failure modes in bi-layered structural components

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Abstract

The problem of crack propagation in bi-layered structural components is addressed. Due to the presence of the bi-material interface and depending on the loading direction, a competition between different crack trajectories (failure modes) can take place. The quantification of the dominant failure mode and of the prevailing fracture mechanism is very often a challenging task, although it is crucial for design purposes. In this contribution, starting from the experimental observation of failure modes in a variety of engineering applications involving bi-layered structural components, an interpretation is proposed in the framework of the finite elements discretization and linear elastic fracture mechanics. The effect of thermo-elastic and residual stresses on the stability of crack propagation is carefully examined. Numerical results confirm the qualitative experimental observations of failure modes in bi-layered structural elements used for rock drilling applications.

Keywords: Linear elastic fracture mechanics; Bi-layered structural components; Fracture mechanisms; Failure modes; Thermo-elastic and residual stresses

1. Introduction

Bi-material structural components are commonly encountered in a variety of engineering applications, such as wear resistant materials, microelectronic devices and composite laminates used in aircraft structures. On the other hand, bonding between heterogeneous materials is a situation occurring not only in advanced and smart materials, like those previously mentioned, but also in traditional materials like concrete when repair systems are used.

During the joining process, interphases having material properties not always intermediate between those of the constituent materials are developed [1,2]. As a result, the mechanical behavior and the overall performance of the component are not limited by the bulk properties, but by the interface characteristics. In fact, according to linear elastic fracture mechanics (LEFM), if a system consisting of two edge-bonded elastic wedges of different materials is considered, a stress concentration or even a singularity can develop at the vertex of the bi-material interface. The severity of the stress-singularity, usually quantified in terms of its order and of the stress-intensity factor, depends both on the elastic bi-material mismatch parameters [3,4] and on the wedge geometry [5–7]. From the practical point of view, the existence of such a stress-singularity means that microfailure processes due to initial defects are likely to occur at the interface.

An additional complexity arising in many interface problems is provided by the presence of significant residual stresses in the region close to the interface. The residual stress field is due to the bonding process itself and it is caused by the different expansion coefficients of the constituent materials and by the elastic mismatch. Moreover, since many engineering components experience thermal loads during their life, significant thermo-elastic stresses have also to be taken into account and superimposed to the residual stresses [8]. The analysis of the effect of residual and thermo-elastic stresses on crack propagation appears to have received a minor attention in the literature, as compared to the more general problem of interface crack propagation.

The aims of this contribution are to foster the use of the finite element (FE) method to structural applications involving interface mechanical problems, as well as to show how it can

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be profitably applied for the fracture mechanics characterization of bi-layered structural components. This research need is in line with the recent attempts in materials science and structural engineering to increase strength and toughness of materials through a full appreciation of material interfaces, their properties and characterization, as also demonstrated by several workshops and special sessions in recent international conferences devoted to interface problems and interface modelling.

In Section 2, starting from the experimental observation of failures taking place in bi-material structural components, a classification of the different failure modes is proposed. This puts into evidence the multidisciplinarity of the research field, since it is shown that the analysis of failure modes in bi-layered structural elements is one of the main concerns not only in civil applications, but also in mechanical and electronic engineering.

In this context, the mathematical and numerical tools required for the structural analysis are defined in Sections 3 and 4, where a numerical formulation of the problem in the FE framework under the hypotheses of LEFM is provided. This approach is adopted for the analysis of brittle crack propagation as well as for fatigue crack growth taking place near or along bi-material interfaces. A particular attention is also devoted to the effect of residual and thermo-elastic stresses on the stability of crack propagation.

Finally, Section 5 shows some new applications in the field of rock drilling, which is kept as a notable example where there is a lack of systematic structural approaches like that proposed in the present paper. The competition among the different failure modes taking place in bi-layered structural components is quantified and expressed in terms of the mechanical properties of the interface and of the constituent materials. These results, particularly important from the engineering point of view, are compared with the qualitative experimental observation of failure modes in wear resistant materials used for rock drilling [9]. The proposed methodology can be, of course, extended to other mechanical problems involving bi-layered structural components, like those reviewed in Section 2.

2. Experimental observation of failure modes and proposed classification

At the scale of the infrastructure, joints and interfaces play a crucial role in the behavior of dams, both in service and failure conditions [10,11]. Physically, they can be classified as follows:

(1) Interfaces between different materials (e.g. concrete and rock).
(2) Construction joints between concrete blocks.
(3) Rock joints or bedding planes in rock masses.

Joints and interfaces may not only affect the mechanical behavior of the dam and its foundation, but also their diffusion properties (flow of liquid water, moisture, temperature, etc.). Since the interface conductivity depends on the opening, and interface tractions depend on water pressure, joints and interfaces may also be the source of coupled phenomena.

For all of these reasons, the problem of mixed-mode fracture of cementitious bi-material interfaces is particularly important. Currently, it is assumed that a crack, once initiated, propagates collinearly along the interface of dam and foundation. However, the experimental observation has not confirmed this behavior and a competition between delamination and crack propagation in one of the material regions takes place. This competition was analyzed by Červenka et al. [12,13], who developed a comprehensive experimental program for carrying out mixed-mode experiments on large-scale simulated bi-material specimens. Considering a crack along the cold joint interface between concrete and rock and using the crack mouth opening displacement as a control parameter, they found that a pure delamination is usually followed by a crack kinking into the rock with a long curvilinear crack path up to the complete failure of the specimen.

Another example of failure modes competition in concrete structures is represented by interfacial debonding in repaired and retrofitted structural elements. In this case, fiber reinforced polymers (FRP) have been widely applied to the strengthening and upgrading of structurally inadequate or damaged concrete beams [14–16]. Due to the fact that structural strengthening is achieved by the interfacial stress transfer from FRP sheets to concrete matrix through the adhesive layer, many efforts have been made in the recent years to control the interfacial bonding/debonding behaviors. In particular, flexural cracks propagate upwards as loading increases, but remain very narrow throughout the loading history. Delamination of the FRP sheets together with a thin layer of concrete takes place only when shear cracks develop close to the support. This failure mode is distinguished from the pure delamination in provisional codes and standards and is referred to as *concrete ripping* [17]. Similar failure modes are also popular with sandwich materials where sub-interface crack propagation [18] and crack path deviation from the interface [19] are very often observed.

Failure modes competition plays a key role also in advanced engineering applications in the field of rock drilling. Polycrystalline diamond (PCD) compact bits composed of an external layer of PCD bonded to a hard metal substrate are used as wear resistant bi-layered structural elements. A detailed overview of the mechanical parameters of these smart materials can be found in [20,21]. Such bi-material elements are joined to a steel support which completes the tool (see Fig. 1(a)).

In a recent paper by Lin et al. [9], wear and failure modes of these compact bits were experimentally investigated. Through a detailed examination of failed samples in either laboratory or field conditions, three primary causes of failure were identified. The first cause was referred to as *chipping* and it is represented by fracture planes more or less parallel to the cutting direction. This type of failure was mainly caused by the action of the (horizontal) cutting force (see Fig. 1(b)). The second failure mode observed by Lin et al. [9] and referred to as *gross fracturing* was mainly caused by overloading in the normal direction due to impacts of the bit on the bottom. Although the crack pattern is often difficult to be distinguished from that due to chipping (opposite starting points), this failure mode was considered as

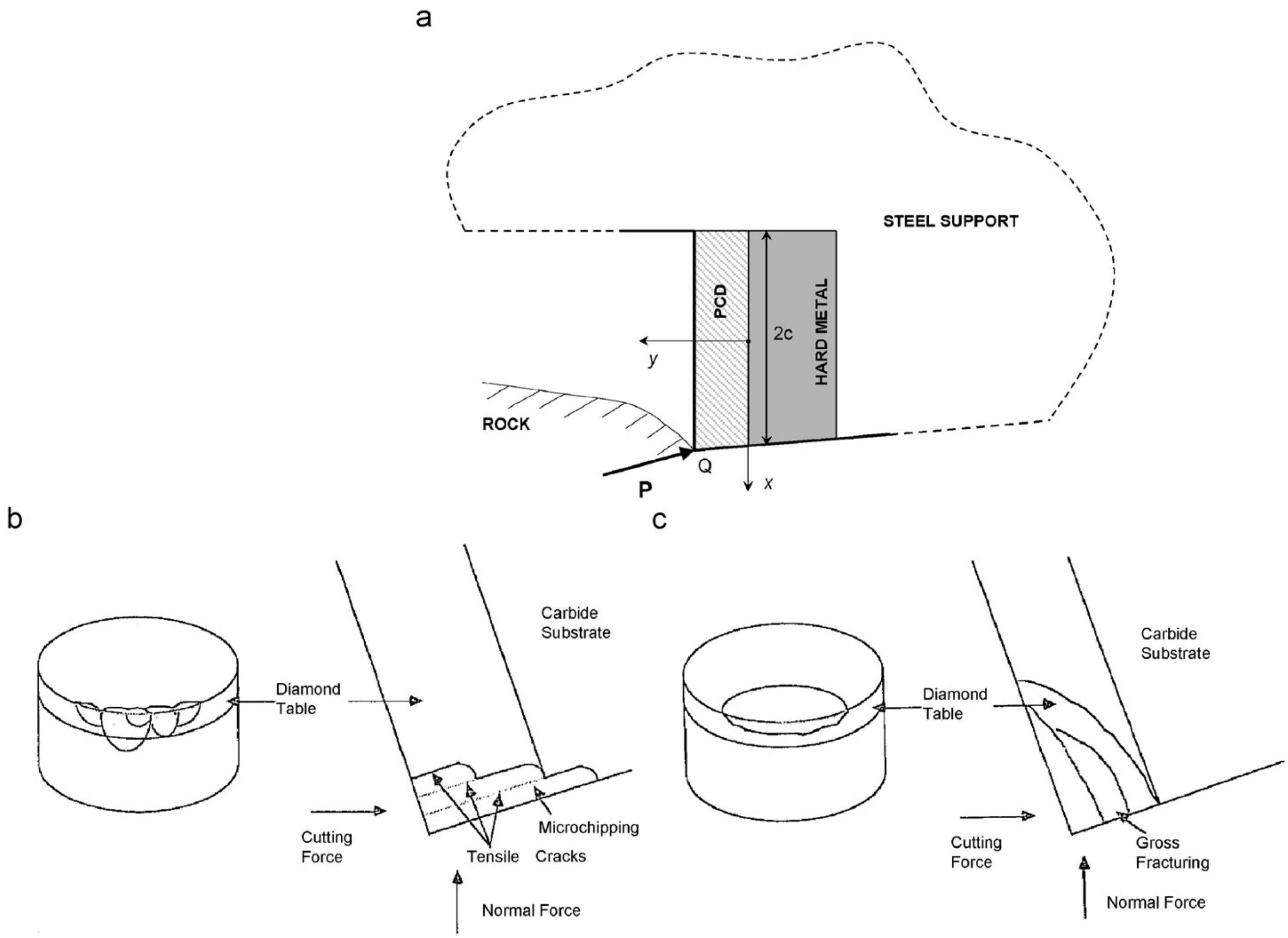

Fig. 1. (a) Sketch of the bi-material system used for rock drilling. Schemes of (b) chipping and (c) gross fracturing failure modes (reprinted from Ref. [9]).

the most severe type of damage, since it usually results in a sudden termination of the bit life. Moreover, it was observed in hard rocks where, because of the high rock hardness, the impact load cannot be spread over a large area (see Fig. 1(c)). Finally, failure due to pure *delamination* was also detected in some cases and it was attributed to the presence of a weak interface between the external layer and the substrate.

Lin et al. [9] observed that the effect of the elastic and thermal mismatches between the two layers can be extremely dangerous due to residual stresses building up at the bi-material interface during joining. However, no quantitative assessment of their effect was provided. Moreover, from those experimental results it clearly emerges that different failure modes can be activated depending on the loading direction. However, at that time it was not possible to recognize neither the dominant fracture mechanism, i.e. brittle of fatigue crack growth, nor the prevailing failure mode. The researchers seem to be very divided about this point. For instance, Dunn and Lee [22] suggested that mechanical overloading of the cutters and a subsequent brittle crack propagation are the main causes of failure. On the opposite, Sneddon and Hall [23] considered fatigue crack growth as a possible dominant fracture mechanism, since cutters are repeatedly subjected to impacts.

This brief review of some experimental results concerning failure of bi-layered elements shows that a competition between failure modes is likely to occur in the majority of bi-material systems used in structural applications. This justifies the possibility to extend the qualitative classification proposed by Lin et al. [9] for the failure analysis of cutters to the more general problem of failure of bi-layered structural components. More specifically, with reference to Fig. 2, the following conventional classification can be proposed:

(1) *Micro-chipping*: This failure is due to a crack whose nucleation point is set along the free edge, very close to the tip of the layered element. The initial crack position ranges from the point Q up to $\frac{1}{10}$ of the interface from the tool tip. This type of failure is caused by the action of a force in the direction perpendicular to the free edge (see Fig. 2(a)).
(2) *Meso-chipping*: As for micro-chipping, this failure is due to a crack whose nucleation point is along the free edge. The initial crack position ranges from $\frac{1}{10}$ up to $\frac{1}{3}$ of the

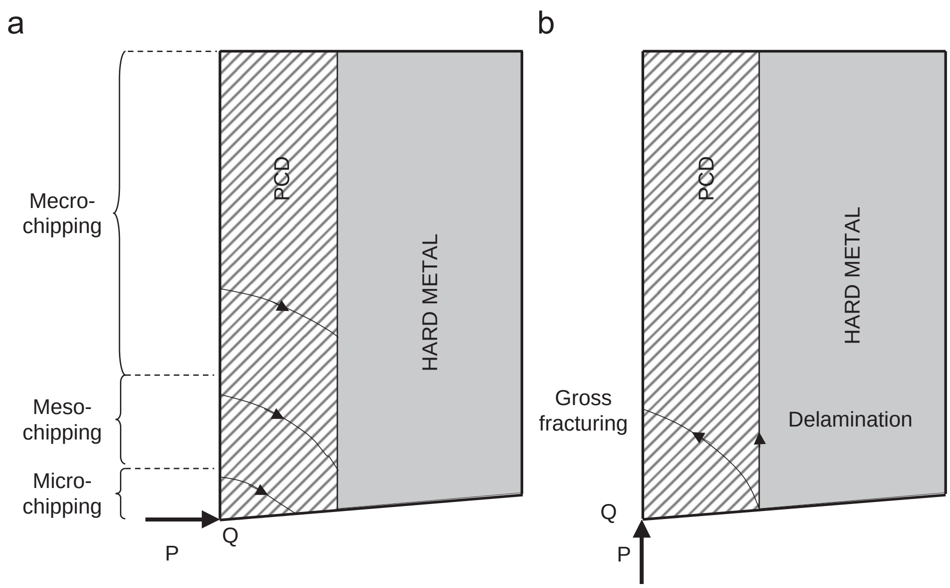

Fig. 2. Sketch of the typical failure modes observed in bi-material structural components.

interface from the tool tip. Also in this case, failure is caused by the action of a force perpendicular to the free edge (see Fig. 2(a)).

(3) *Macro-chipping*: This failure mode can be distinguished from micro- and meso-chipping for the nucleation point which is placed along the free edge and ranges from $\frac{1}{3}$ up to the total free edge length. Also in this case, failure is caused by the action of a force perpendicular to the free edge (see Fig. 2(a)).

(4) *Gross fracturing*: This failure mode gives rise to a curvilinear crack path in the external layer and is caused by overloading in the vertical direction, i.e. in the direction collinear to the interface. The activation point may range from the tool tip up to the bi-material interface (see Fig. 2(b)).

(5) *Delamination*: As a particular case of gross fracturing with crack nucleation exactly at the bi-material interface, in this case crack propagation takes place vertically along the interface (seeFig. 2(b)).

In order to propose a quantitative analysis of the competition existing among these failure modes, a numerical method based on the FE discretization and on LEFM is discussed in the next section.

3. Crack propagation criteria

When fracture involves bi-material interfaces, specific crack propagation criteria have to be considered. Among the criteria generally used, a distinction has to be made between local and global criteria.

Local fracture criteria can be used in those cases where the elastic fields lose self-similarity or the crack may not remain coplanar as it propagates [24]. These criteria are based on quantities related to the series expansion of the elastic fields in the neighborhood of the crack tip. For brittle materials, an example of a local fracture criterion is represented by the modified version of the Erdogan and Sih [25] maximum circumferential stress criterion proposed by Piva and Viola [26] for the study of an elastic system consisting of two bonded dissimilar materials with a crack along the interface. The following assumptions are made in this model:

(1) Crack propagation will take place along the interface or in one of the two adjacent materials along the direction $\theta_0^{(i)}\,(i=1,2)$ for which the circumferential stress, evaluated at a small distance r_0 from the crack tip, is maximum.

(2) Crack propagation will begin as soon as one of the following conditions is satisfied:

$$\begin{aligned}
&\sqrt{2\pi r_0}\,\sigma_\theta^{(1)}(\theta_0^{(1)}, r_0) = K_{\mathrm{IC}}^{(1)}, \quad 0 < \theta_0^{(1)} \leqslant \pi,\\
&\sqrt{2\pi r_0}\,\sigma_\theta^{(2)}(\theta_0^{(2)}, r_0) = K_{\mathrm{IC}}^{(2)}, \quad -\pi \leqslant \theta_0^{(2)} < 0,\\
&\sqrt{2\pi r_0[\sigma_\theta^2(0, r_0) + \tau_{r\theta}^2(0, r_0)]} = K_{\mathrm{int}},
\end{aligned} \tag{1}$$

where $K_{\mathrm{IC}}^{(1)}$ and $K_{\mathrm{IC}}^{(2)}$ are the critical stress-intensity factors of the two components and K_{int} is a critical parameter taking into account the adhesive interface bonding strength.

On the other hand, global fracture criteria are essentially based on the energy balance and are generally applicable under the condition that the crack propagates along an interface or in the same homogeneous medium in its own plane [27]. Applications to the study of mixed-mode crack problems were also proposed by Gupta [28].

For instance, let us consider the problem consisting of a crack which starts at the interface between two different materials. Clearly, two possibilities may occur during propagation: to continue to move along the interface giving rise to a pure delamination, or to move out of the interface into one of the two material regions. According to He and Hutchinson [27] and to He et al. [29], it is possible to assume that the interface, like a continuum, presents a resistance to cracking, i.e. a critical interface fracture energy $\mathscr{G}^i_{\rm IC}$. In this respect, the conditions for pure delamination along the bi-material interface, or for deflection into one of the material regions, can be stated using a strain energy-based failure criterion. In doing so, we consider first the ratio between the strain energy release rate for delamination and the critical interface fracture energy, $\mathscr{G}_{\rm del}/\mathscr{G}^i_{\rm IC}$, and then the ratio between the strain energy release rate for crack deflection into one of the constituent materials and the corresponding critical value of the strain energy release rate, $\mathscr{G}_{\rm def}/\mathscr{G}_{\rm IC}$. The crack continues to propagate along the interface if

$$\frac{\mathscr{G}_{\rm del}}{\mathscr{G}^i_{\rm IC}} > \frac{\mathscr{G}_{\rm def}}{\mathscr{G}_{\rm IC}}, \tag{2}$$

otherwise it deflects into one of the neighborhood materials.

This failure criterion was implemented in the FE FRActure ANalysis Code (FRANC2D) by Ingraffea and Wawrzynek [30,31] according to the following algorithm:

(1) For each material region around a crack tip:
   - find the direction of the maximum tensile circumferential stress;
   - remesh to add a finite crack increment in this direction;
   - solve the resulting FE equations;
   - normalize the global change in strain energy with respect to the crack increment and compute the ratio with the critical energy release rate.

(2) For each interface around the crack tip:
   - extend the crack a finite distance along the interface;
   - solve the resulting FE equations;
   - use the relative opening and sliding at the crack tip to determine the load angle and the critical strain energy release rate;
   - normalize the change in strain energy with respect to the crack increment and find the ratio with the critical strain energy release rate.

(3) The direction of propagation is that with the largest associated ratio of the rate of energy release to the critical rate of energy release.

FE simulations are performed in the present study according to the second approach. For crack propagation inside homogeneous materials, the global and the local criteria give predictions that fall in a very narrow band, see [32]. On the other hand, for interface crack propagation problems, the use of the energy balance criterion is motivated by the numerical comparisons proposed by Červenka et al. [13]. They showed that, for the portion of crack growth along the bi-material interface, the energy release rate tends to remain almost constant, contrarily to the stress-intensity factors related to circumferential and shearing stresses that are functions of the crack length. Therefore, from the numerical point of view, the energy balance criterion is considered to be more robust and appropriate for interface crack simulations. In addition, bi-material interfaces are usually characterized from the fracture mechanics point of view by experimentally evaluating their critical interface fracture energy, rather than in terms of a critical stress-intensity factor. This is especially true for fatigue crack growth simulations, where modified versions of the Paris' law are written in terms of strain energy release rate range instead of the stress-intensity factor range (see e.g. [33]).

4. Numerical modelling of thermo-elastic and residual stresses

An additional complexity arising in many interface problems is provided by significant residual and/or thermo-elastic stresses present in the region close to the interface. The residual stress field is generally due to the bonding process and it is caused by the different expansion coefficients of the two constituent materials and by the elastic mismatch. On the other hand, many engineering components experience thermal loads during their life and significant thermo-elastic stresses have to be taken into account. Hence, the applied thermal loads, together with the mechanical forces acting on the structure, may result in a crack nucleation and growth.

Multi-layered elements used for mechanical and electronic applications are usually subjected to nonuniform temperature distributions during their life. As a consequence, a solution of a preliminary steady-state thermal problem is often required to estimate the temperature distribution within the structural elements. The problem is governed by the Fourier heat equation [34]:

$$\nabla^T[\mathbf{K}\nabla T] + Q = \rho c \frac{\partial T}{\partial t}, \tag{3}$$

where $\mathbf{K}$ is the thermal conductivity tensor, ∇ is the gradient operator, Q is the heat production rate per unit volume, ρ is the mass density and c is the specific heat.

Residual stresses are instead generated during the bonding process and are usually caused by a uniform temperature distribution. From the theoretical point of view, it is important to notice that the problem of residual stresses induced by a hot bonding of two material components during the fabrication process can be considered equivalent, neglecting the algebraic sign, to the problem of thermal stresses induced by a temperature increase in a bonded two-material structure [35]. As a consequence, the problem of residual stresses induced in the elements by a temperature increase ΔT can be studied as the problem of thermal stresses due to a temperature decrease of the same absolute amount.

In this respect, the competition between residual and thermo-elastic stresses can be favorable, since these stress fields can totally compensate each other if the bi-material elements are subjected to the same temperature excursion and distribution as that applied during fabrication. This result implies that the critical conditions for these components are usually attained during the first stage of their life, when residual stresses are prevailing. On the other hand, only a partial compensation can be obtained when the temperature distribution in service does not match exactly that due to the bonding process.

5. Numerical examples

In this section we propose the application of the FE method to the quantitative assessment of the competition among the different failure modes. Both fracture mechanisms, i.e. brittle crack propagation and fatigue crack growth, are separately addressed. As a representative case study, we focus our attention on the analysis of failure modes observed in bi-material structural elements used for rock drilling. The values of the fracture toughness, K_{IC}, of the external layer and of the substrate are equal 10 and 30 $\mathrm{MPa}\sqrt{\mathrm{m}}$, respectively.

The numerical simulations have been performed under plane stress conditions using the public domain FE program FRANC2D, which allows to perform incremental fracture analyses. Eight-noded isoparametric FEs are used for the discretization of the continuum. This choice is fully consistent with earlier numerical applications of the code to crack propagation problems in structural elements consisting in joined dissimilar materials, see e.g. the examples in [31,36,37]. Details of the problem of remeshing associated with crack growth near or at bi-material interfaces, as well as of the use of special singular FEs at the crack tip, are also available in [31,38]. More specifically, quarter-point singular elements are adopted at the crack tip inside homogeneous materials, as routinely done in these situations [39,40]. On the other hand, special transition elements are used when the crack tip lies along a bi-material interface, to obtain accurate evaluations of the stress field and to preserve the internal material boundaries when remeshing during crack propagation (see [31] for a discussion on their accuracy and validation).

5.1. Brittle crack propagation

High residual stresses develop during the manufacturing process of the bi-layered structural elements used for rock drilling. Due to the temperature decrease after bonding, a residual compressive stress takes place in the external layer and a residual tensile stress develops in the hard metal substrate. These stresses are due to the difference in thermal expansion coefficients and mechanical properties of the two layers. Residual stresses increase when the temperature falls, whereas when the temperature rises, as it occurs during drilling, high tensile stresses are induced in the external layer and a reduction of residual stresses should be expected.

In order to confirm this prediction, a uniform temperature distribution due to bonding is superimposed to the nonuniform temperature distribution experienced in service, during the normal use of the tool. The former distribution assumes a uniform temperature variation equal to $\Delta T = -500\,°\mathrm{C}$, whereas the latter is estimated by performing a preliminary steady-state thermal analysis with a temperature increment equal to $\Delta T = 450\,°\mathrm{C}$ locally imposed at the tool tip (see heat flux and temperature boundary conditions in Fig. 3(a)). By assuming an isotropic thermal conductivity for each material, the computed temperature distribution representative of the drilling condition is depicted in Fig. 3(b).

Residual tangential stresses along the interface, τ^{RES}, thermo-elastic stresses, τ^{TH}, and the superimposed total tangential stresses, $(\tau^{RES} + \tau^{TH})$, can be computed on the basis of the kinematic boundary conditions shown in Fig. 3(c) and are depicted in Fig. 4. Thermo-elastic stresses can also be analytically estimated according to Ref. [8] and are superimposed to Fig. 4 with dashed line for comparison. The parameter x/c denotes the relative position along the interface and the intersection of the interface with the free edge of the bi-layered element corresponds to $x/c = 1$ (see Fig. 1(a)). The tangential residual stress at the interface is symmetric and reaches its maximum value at the free ends. Thermo-elastic stresses have an opposite sign with respect to the residual ones and a lack of symmetry due to the nonsymmetric temperature distribution in the element can be observed. At the free edges the residual stress prevails with respect to the thermal one and, due to the competition, a reduction by one-third of the residual tangential stress occurs. As previously mentioned, the stress is globally negligible in the remaining points along the interface (see also the dotted line in Fig. 4).

5.1.1. Chipping failure modes

Chipping failure modes are numerically modelled by considering the limit problem of a horizontal force acting at the tool tip. This loading case represents, in fact, the worst condition for crack nucleation and propagation from the vertical edge of the element parallel to the interface (see Figs. 1(b) and 2(a)).

Three positions of the initial crack along the free edge are considered in order to simulate different levels of chipping. To be more specific, micro-chipping is simulated by setting the initial crack position close to the element tip, whereas macro-chipping is investigated by considering the crack tip position in the middle of the free edge. An intermediate position giving rise to meso-chipping is also considered. Initial crack lengths are set equal to those of existing defects typically observed in the microstructure of the external layer [41].

In these analyses, the critical value of the horizontal impact force, P_c, is not set *a priori*, but it is computed at each step by enforcing the condition for crack propagation, i.e. $\mathcal{G}_I = \mathcal{G}_{IC}$ at the crack tip. This solution scheme allows us to investigate on the stability of crack growth.

Deformed meshes during chipping failure modes are shown in Fig. 5. Considering $P^* = 2000\,\mathrm{N}$ as the typical peak value of the impact force experienced during experimental tests [22], the nondimensional critical load corresponding to crack propagation, P_c/P^*, is depicted in Fig. 6 as a function of the relative crack depth, a/a_{max}, where a_{max} denotes the crack length at failure, i.e. when the external layer is completely cracked.

In each of these failure modes, unstable crack propagation occurs, since the external load has to be progressively reduced during crack propagation. Furthermore, we can notice that the farther the crack tip from the tool tip, the higher the critical load for crack propagation. This fact is due to the high stress level in the region close to the point of application of the external load. These boundary effects cannot be evaluated by modelling the tool as a bi-layered beam and adopting the classical beam theory.

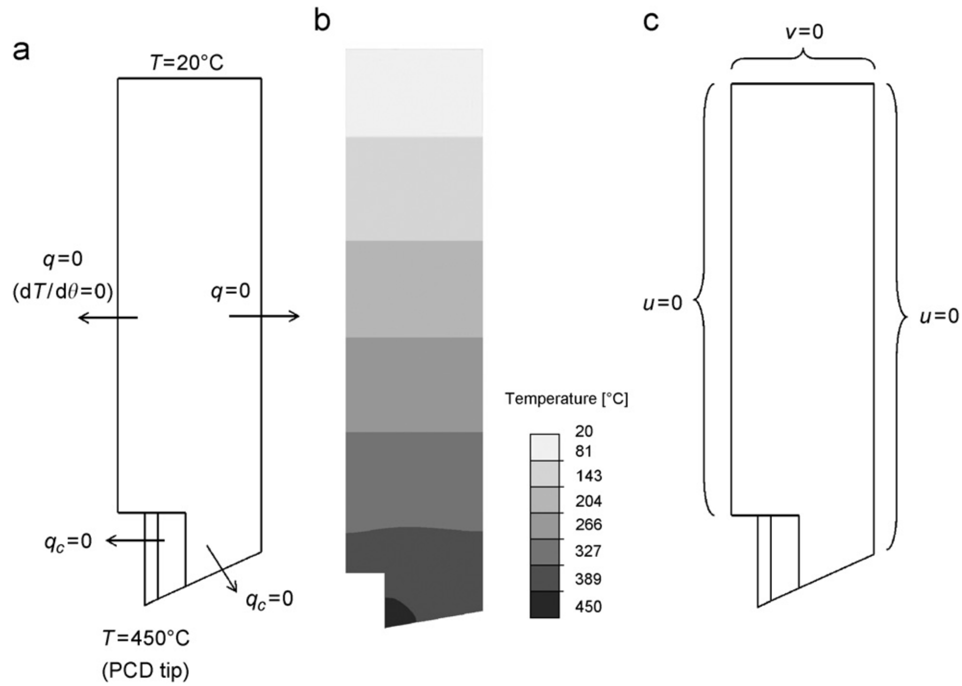

Fig. 3. Steady-state thermal analysis: (a) thermal boundary conditions, (b) computed temperature distribution and (c) kinematic boundary conditions.

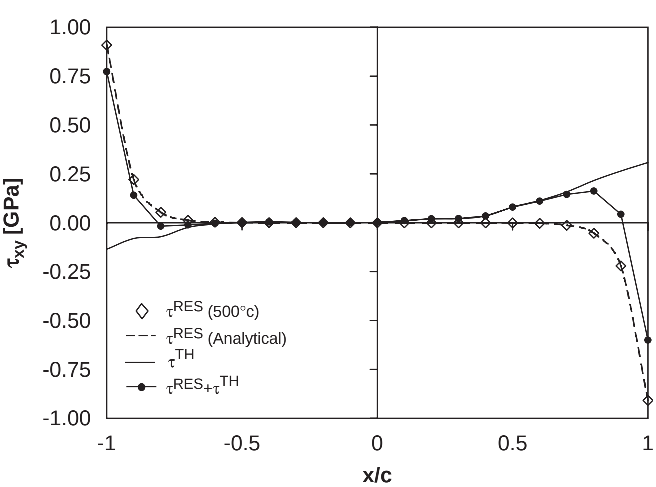

Fig. 4. Tangential stress along the interface.

The critical load for meso- and macro-chipping is greater than the usual applied forces. This fact is in good agreement with the experimental results by Lin et al. [9], who observed that macro-chipping should be due to some mechanical fatigue mechanism rather than to single impacts.

The effect of thermo-elastic and residual stress fields can be quantitatively estimated by comparing dashed lines with solid lines in Fig. 6 (see also the deformed meshes and the contour plot of the maximum principal stress reported in Fig. 7). An opposite effect on micro- and macro-chipping failure modes has to be noticed: in the former case, residual and thermal stresses have an unfavorable effect, because they reduce the value of the critical load, P_c, whereas in the latter they play a useful role. This phenomenon is basically due to the fact that the thermal stress field is not uniform within the structural component and higher compressions take place towards the upper part of the element (see Fig. 7).

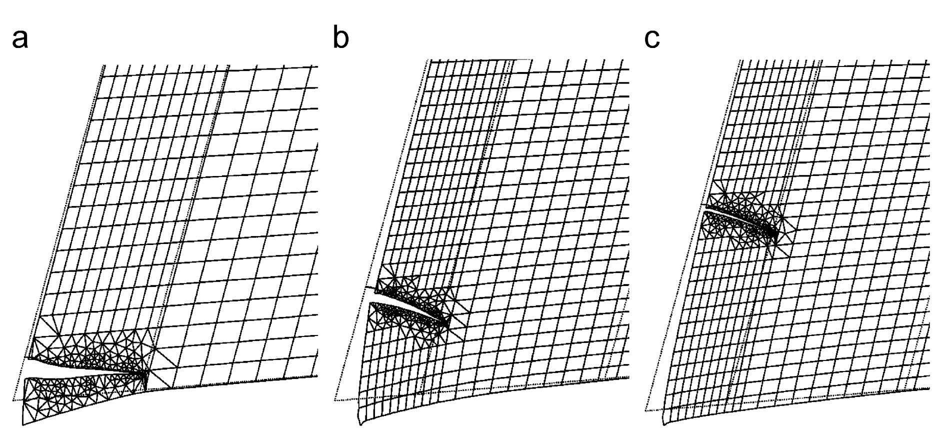

Fig. 5. Deformed meshes during micro-, meso- and macro-chipping.

5.1.2. Gross fracturing and delamination

According to LEFM, if a system consisting of two edge-bonded elastic wedges of different materials is considered, a stress-singularity can result at the intersection of the bi-material interface with external boundary, even in the absence of a re-entrant corner [6]. The singular components of the stress field can be written as follows:

$$\sigma_{ij} = K^* r^{\mathrm{Re}\,\lambda - 1} f_{ij}(\theta), \tag{4}$$

where K^* is referred to as *generalized stress-intensity factor* [42]. The parameter λ defines the order of the stress-singularity and its real part is comprised between 0 and 1, whereas function f_{ij} is the eigenfunction of the problem and locally describes the angular variation of the stress field near the singular point O. Both λ and f_{ij} can be determined according to an asymptotic analysis as fully described in [43,44] and depend on the boundary conditions imposed in proximity of the singular point, on the junction geometry and on the elastic mismatch between the joined materials.

From a practical point of view, the existence of such a stress-singularity means that microfailure processes due to initial defects are likely to occur at the interfaces.

Moreover, as observed by Munz and Yang [45], in the case of vanishing singular stress exponent, i.e. for $\mathrm{Re}\,\lambda_j = 1$, the regular term component of the stress field which depends on the thermal mismatch tends to infinity in its turn. This result implies that the regular term in thermo-elastic material junctions can be extremely significant and it can provide an important contribution to the interface normal stress distribution also for cases of weak material mismatch leading to $\mathrm{Re}\,\lambda_j \cong 1$.

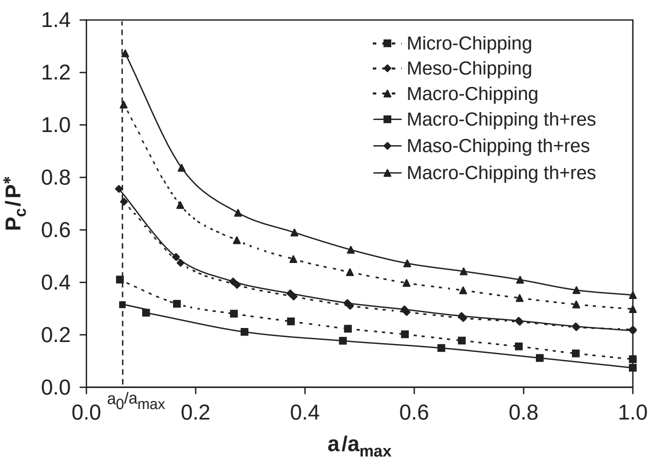

Fig. 6. Brittle crack propagation for chipping failure modes.

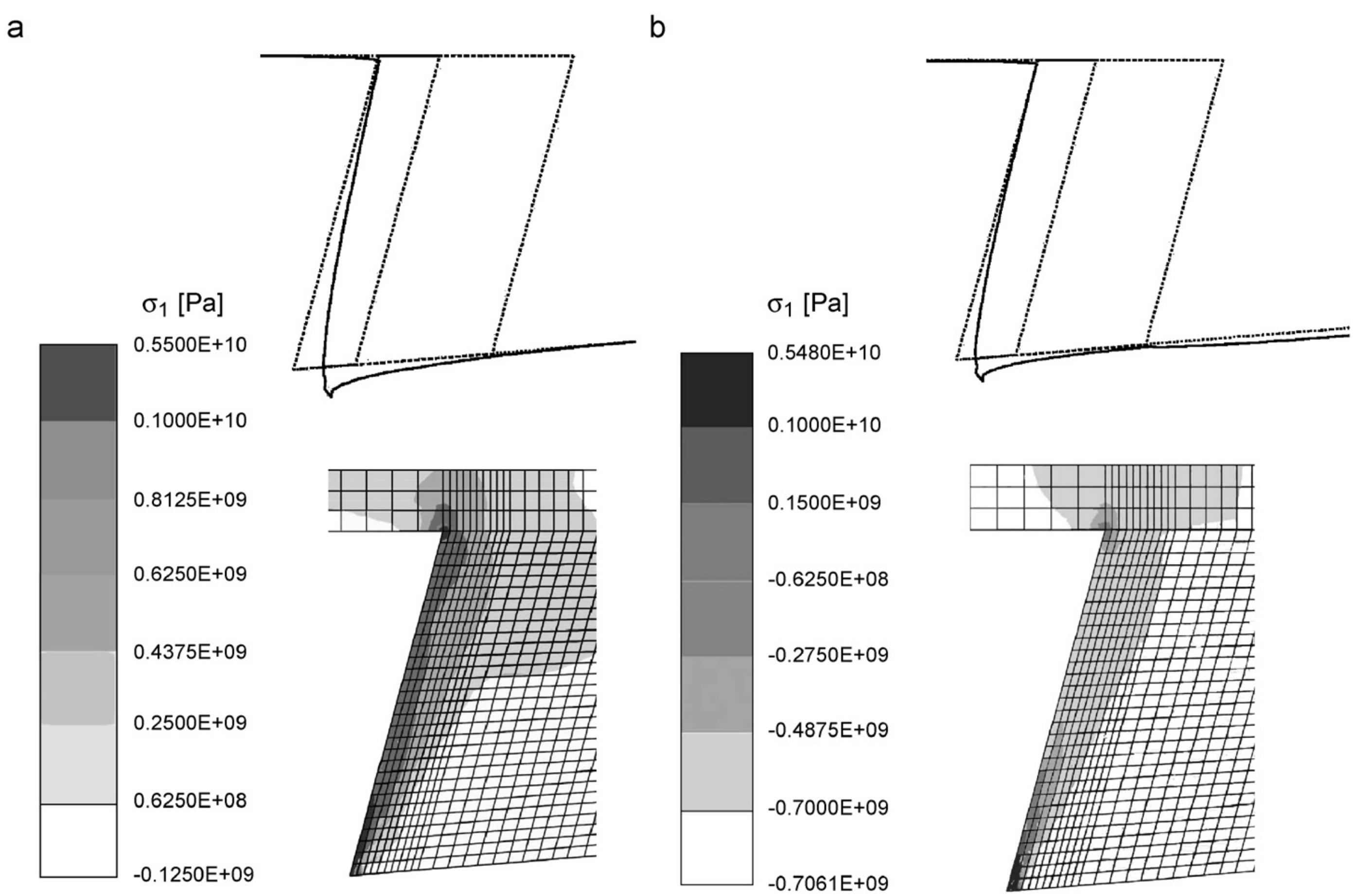

Fig. 7. Deformed meshes and contour plot of the maximum principal stress in case of (a) a horizontal force only and (b) with superimposed thermo-elastic and residual stress fields.

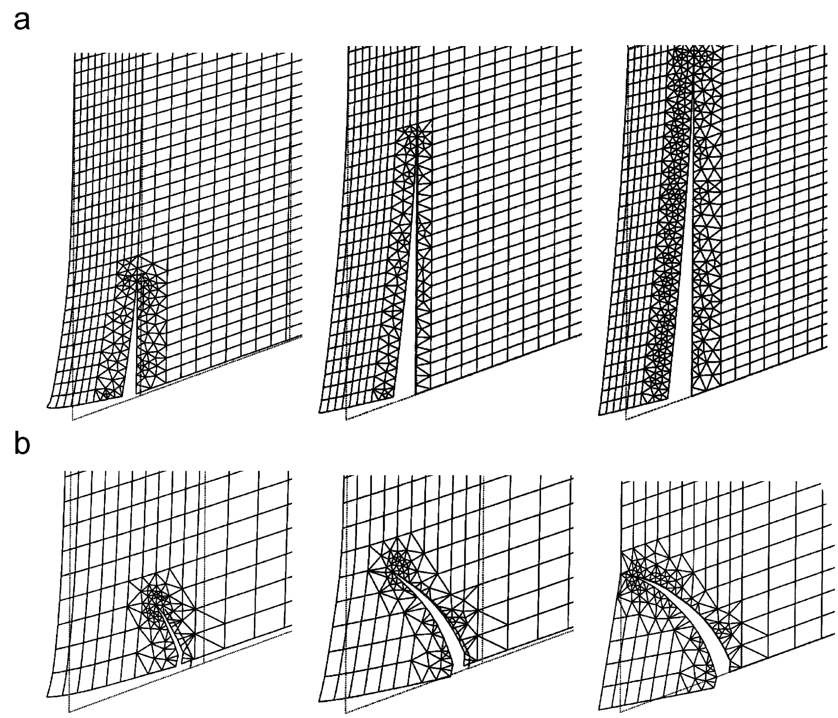

Fig. 8. Deformed meshes during (a) delamination and (b) gross fracturing.

By considering an initial crack which nucleates from the bi-material interface, the problem of brittle crack propagation is addressed. In these numerical simulations, the initial crack length is set equal to that of pre-existing defects in these materials, i.e. $a_0 = 50\,\mu\text{m}$. Since gross fracturing and delamination are activated by loading conditions in which the vertical component of the force is prevalent, we analyze the most severe loading condition represented by a pure vertical force applied to the tool tip. Also in this study, the external load is not set *a priori*, but it is computed at each step by enforcing the condition for crack propagation. In this way, stable or unstable crack propagations can be easily controlled.

As previously discussed, the conditions for pure delamination along the bi-material interface, or for deflection into one of the material regions, are given by a strain energy release rate-based failure criterion. In other words, the more suitable crack propagation direction is ruled by an energy criterion. As a result, in the present case study we notice a competition between two different crack trajectories. From numerical investigations, we observe in fact that only a competition between delamination or deflection into the external layer is the real possibility, whereas deflection into the substrate is not permitted due to its high fracture toughness. Crack deflection into the external layer gives rise to a curvilinear chipped region which resembles the experimentally detected gross fracture failure mode.

Furthermore, we observe that brittle crack propagation along the interface can occur only if the interface toughness is less than approximately one-third of that of the external layer. Roughly speaking, gross fracturing prevails with respect to delamination in the case of normal interfaces. On the contrary, when the interface is extremely weak, the nondimensional critical load for delamination is less than that for gross fracturing and crack propagation along the interface should prevail with respect to a crack deflection inside the external layer. These results are in good agreement with the experimental observations.

Assuming the limit case of a weak interface, brittle delamination is simulated and the deformed meshes are shown in Fig. 8(a). On the other hand, by assuming a normal interface, i.e. the interface toughness has an intermediate value between those of the neighborhood materials, a deflection into the external layer is simulated. Deformed meshes during crack propagation are shown in Fig. 8(b).

In both cases, the nondimensional external load for crack propagation, P_c/P^*, is computed at each step and depicted in Fig. 9 in terms of the nondimensional crack length, a/a_{max}. Critical loads for crack propagation in the absence of thermo-elastic and residual stress fields are also shown in the same diagrams for each failure mode (see dashed lines). In these diagrams the parameter a_{max} denotes the maximum crack length for each failure mode corresponding to a broken external layer for gross fracturing, or to the total interface length in the case of pure delamination, respectively.

Unstable crack propagations take place for both failure modes, since the external load has to be reduced at each step. In spite of the fact that the crack trajectories with or without thermo-elastic and residual stress fields are approximately the same, the critical load for crack propagation is significantly influenced by their presence. In the case of gross fracturing, it is reduced by a factor of 2, whereas that corresponding to delamination is slightly increased.

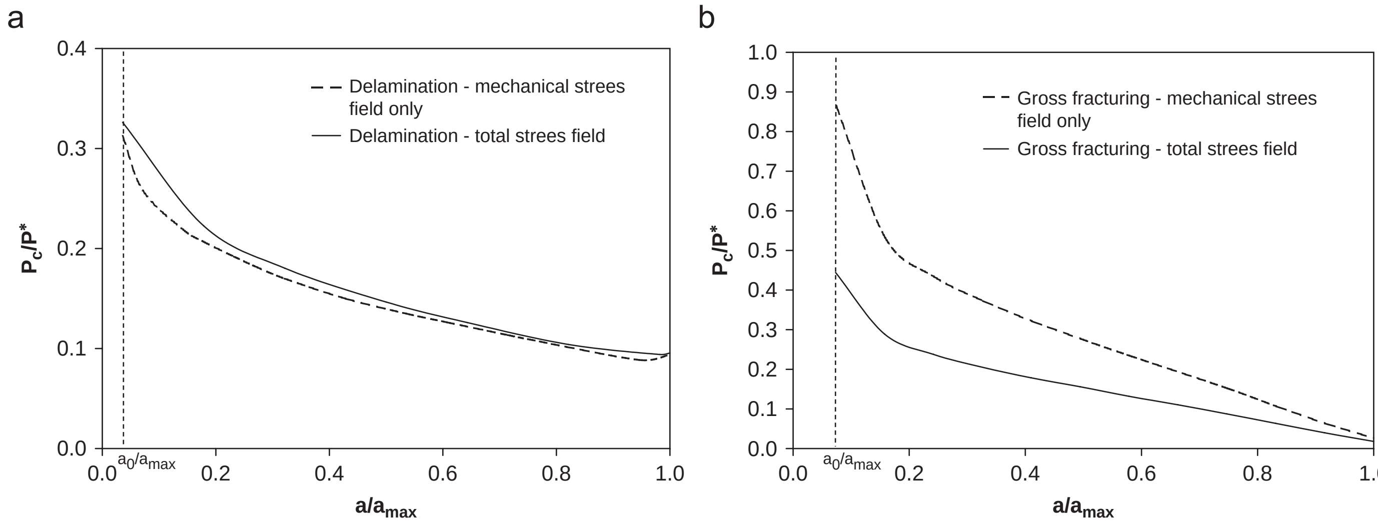

Fig. 9. Nondimensional critical load vs. nondimensional crack length: (a) delamination and (b) gross fracturing.

5.2. Fatigue crack growth

Fatigue crack growth can be studied according to the well-known Paris' law:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K_{\mathrm{I}})^m, \tag{5}$$

where a denotes the crack length, N is the number of loading cycles, $\Delta K_{\mathrm{I}} = K_{\mathrm{I}}(\max) - K_{\mathrm{I}}(\min) = (1-R)\,K_{\mathrm{I}}(\max)$ and C and m are empirical constants.

In this study the parameter C has been correlated to the material fracture toughness, following the method proposed in [33]. For interface crack propagation, Eq. (5) has been rewritten in terms of the strain energy release rate range, instead of the stress-intensity factor range, as shown in [33]. The parameter m is equal to unity and the loading ratio R is set equal to zero. Applying Paris' law and numerically computing the values of the stress-intensity factors, we obtain by integration the crack length as a function of the cycles number, i.e. $a = a(N)$.

Residual and thermo-elastic stresses are not considered in the numerical simulations since they are static and permanent loads and the crack trajectories are slightly influenced by them.

5.2.1. Chipping failure modes

Chipping failure modes analyzed in the previous section are studied also from the fatigue point of view. The tool tip is subjected to cyclic horizontal impact forces of amplitude equal to P^*.

The nondimensional crack length is reported as a function of the cycles number in Fig. 10(a). The comparison among the crack propagations corresponding to three different chipping failure modes shows that the fatigue life ranges between 9000 and 15,000 cycles, depending on the initial crack tip position. Cracks near the tool tip are more severe than others.

5.2.2. Gross fracturing and delamination

Gross fracturing and delamination are simulated in this section from the fatigue point of view. In this case the tool tip is subjected to cyclic vertical impact forces of amplitude equal to P^*.

According to the experimental evidence showing the presence of sub-interfacial crack propagation in the PCD, the interface fracture toughness is assumed to be equal to that of the external layer. Fig. 10(b) shows that the fatigue life after pure delamination is longer than that after gross fracturing. However, the delamination of one-tenth of interface already occurs after approximately the same amount of cycles as in the other failure modes. Fatigue life after gross fracturing has the same order of magnitude as that after micro-chipping.

5.3. Prevailing failure modes and fracture mechanisms

Five failure modes in wear resistant bi-material structural components have been numerically simulated: micro-, meso- and macro-chipping, gross fracturing and delamination. Chipping failure modes are mainly caused by the application of horizontal impact forces, whereas gross fracturing and delamination are due to vertical loads. All the above failure modes have also been experimentally observed by Lin et al. [9] during rock cutting.

From the numerical results it emerges that, in the case of chipping failure modes, small flakes break off with the plane of fracture being approximately parallel to the direction of cut. Fractures initiate in the external layer and then propagate towards the bi-material interface, giving rise to a chipped zone which may include the substrate. Furthermore, it has to be noticed that, in the case of meso- and macro-chipping, the critical loads for brittle crack propagation corresponding to the initial crack length a_0 are higher than usual cutting forces. As a result, this type of damage is most probably due to fatigue rather than to single impacts. Fatigue crack growth simulations suggest

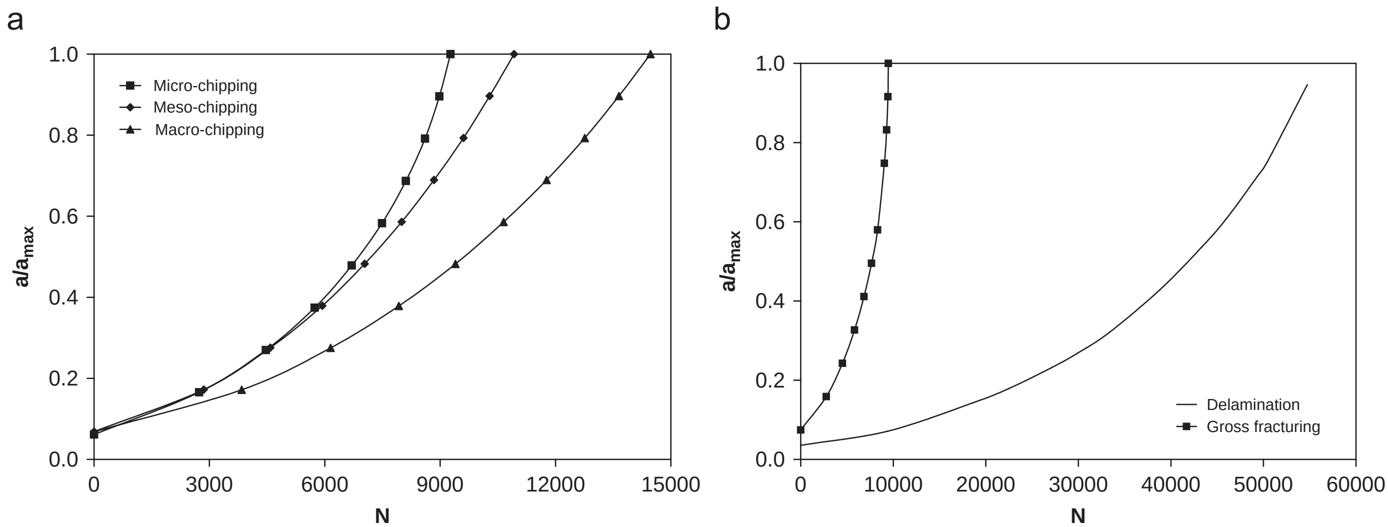

Fig. 10. Fatigue crack propagation for (a) chipping failure modes and (b) gross fracturing and delamination.

Table 1
Prevailing fracture mechanism for each failure mode

Failure mode	Prevailing fracture mechanism	Remarks
Micro-chipping	Brittle crack propagation	Competition with wear; wear is favorable
Meso-chipping	Fatigue crack growth	Fatigue life between 9000 and 15,000 cycles
Gross fracturing	Brittle crack propagation	Typical of not worn cutters; thermo-elastic and residual stresses are unfavorable: P_c reduced by 50%
Delamination	Brittle crack propagation Fatigue crack growth	Weak interfaces only (manufacturing defects) $\frac{1}{10}$ of the interface delaminated after 10,000 cycles

a fatigue life in the range from 9000 to 15,000 cycles. Experimental results by Lin et al. [9] are in good agreement with respect to our conclusions. On the contrary, as regards micro-chipping, an initial value of P_c close to usual cutting forces was obtained. Thermo-elastic and residual stress fields have an unfavorable effect and we should expect to observe this type of failure just after the first impact. Most likely, a competition between micro-chipping and wear takes place. In fact, worn flanks produce a change in the direction of the impact force and reduce the dimension of the region subjected to micro-chipping.

As far as gross fracturing is concerned, Lin et al. [9] observed that it takes place over a very short time period. This damage usually occurs when the base material changes and the cutter runs into a stronger rock or against a steel bar. Cracks nucleate on the curved (cylindrical) surface of the cutter and propagate towards the center, removing a circular chip whose fracture plane is initially almost normal to the cutting direction. Due to the shape of the fractured surface, it is supposed that this failure mode is mainly or solely due to the cutting vertical force. From numerical simulations of brittle crack propagation, we have observed very low values of the initial critical load for crack propagation, $P_c(a_0)$, and a harmful role played by thermo-elastic and residual stresses. Since this type of failure is observed for some cutters that have worked very shortly and have not yet experienced wear [9], the cause of this damage can be usually attributed to mechanical overload.

As for gross fracturing, also delamination is mainly due to impact forces in the vertical direction. This type of damage has a less frequent experimental occurrence. Hence, we conclude that brittle delamination along the interface can only occur in the case of manufacturing defects giving rise to extremely weak interfaces. A fatigue mechanism is then dominant for this mode and the numerical results suggest that a delamination of one-tenth of the interface may occur after 10,000 cycles, a result which is in good agreement with the experimental observations. A summary of the above results, as well as a detailed comparison, is presented in Table 1.

In conclusion, as far as brittle crack propagation is concerned, gross fracturing represents the most dangerous failure mode, whereas meso-chipping is the most critical type of damage in the case of fatigue crack growth. Failure due to gross fracturing affects not worn cutters only and it can be partially avoided by changing the cutter geometry. On the other hand, due to meso-chipping, fatigue crack growth can only be reduced by changing the material microstructure (see also Table 2).

Table 2
Prevailing failure modes for each fracture mechanism

Fracture mechanism	Prevailing failure mode	Remarks
Brittle crack propagation	Gross fracturing	P_c due to gross fracturing is 30% of P_c due to micro-chipping and 10% of P_c due to macro-chipping
Fatigue crack growth	Meso-chipping	Fatigue life for meso-chipping is 20% of that for complete delamination

6. Conclusions

Bi-layered structural components are used in several civil, mechanical and electronic engineering applications. In many cases the residual stresses developed during the joining process are particularly relevant and need be considered in the structural analysis. When these components are subjected to mechanical loading, existing defects in the material microstructure may propagate with the subsequent failure of the element. Moreover, thermo-elastic stresses can also be important due to heating. As a result, depending on the loading direction and on the mechanical properties of the interface and of the constituent materials, failure in these elements often encompasses different crack trajectories. However, they are not equally dangerous and a full appreciation of their criticality is extremely crucial for design purposes.

In this study, the problem of brittle crack propagation and fatigue crack growth in bi-material structural components has been addressed in the framework of the FE discretization. Separately considering different crack nucleation points, the possible failure modes have been simulated and compared. The prevailing fracture mechanism has been determined for each failure mode. Conversely, for each fracture mechanism, the prevailing failure mode has been individuated. The effect of thermo-elastic and residual stresses has been quantified in terms of stability of crack propagation.

From the engineering point of view, it has to be remarked that our proposed methodology is particularly effective, since it permits to define the true possible critical modes and mechanisms of damage. The obtained results for the proposed case study are in good agreement with the qualitative experimental observation of failure modes in bi-material compact bits used for rock drilling [9]. In this field, for example, there is an evident lack of systematic approaches and most of the contributions available in the literature focus on the discussion of experimental tests. The present methodology can be profitably extended to similar mechanical applications involving bi-layered structural elements that are usually optimized with trial and error methods, rather than with predictive approaches.

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References

[1] P.A. Kakavas, N.K. Anifantis, G.C. Papanicolaou, Role of imperfect adhesion on thermal expansivities of transversely isotropic composites with an inhomogeneous interphase, Composites Part A 29 (1998) 1021–1026.
[2] S. Mukherjee, C.R. Ananth, N. Chandra, Effects of interface chemistry on the fracture properties of titanium matrix composites, Composites Part A 29 (1998) 1213–1219.
[3] J. Dundurs, Discussion of edge-bonded dissimilar orthogonal elastic wedges under normal and shear loading, ASME J. Appl. Mech. 36 (1969) 650–652.
[4] J. Dundurs, Effect of elastic constants on stress in a composite under plane deformation, J. Compos. Mater. 1 (1967) 310–322.
[5] D.B. Bogy, Edge-bonded dissimilar orthogonal elastic wedges under normal and shear loading, ASME J. Appl. Mech. 25 (1968) 460–466.
[6] D.B. Bogy, Two edge-bonded elastic wedges of different materials and wedge angles under surface tractions, ASME J. Appl. Mech. 38 (1971) 377–386.
[7] V.L. Hein, F. Erdogan, Stress singularities in a two-material wedge, Int. J. Fract. Mech. 7 (1971) 317–330.
[8] M.P. Rodriguez, N.Y.A. Shammas, Finite element simulation of thermal fatigue in multilayer structures: thermal and mechanical approach, Microelectron. Reliab. 41 (2001) 517–523.
[9] T.-P. Lin, M. Hood, G.A. Cooper, X. Li, Wear and failure mechanisms of polycrystalline diamond compact bits, Wear 156 (1992) 133–150.
[10] A.R. Ingraffea, Case studies of simulation of fracture in concrete dams, Eng. Fract. Mech. 35 (1990) 553–564.
[11] L.F. Martha, J. Llorca, A.R. Ingraffea, M. Elices, Numerical simulation of crack initiation and propagation in an arch dam, Dam Eng. 3 (1991) 193–214.
[12] J. Červenka, J.M. Chandra Kishen, V.E. Saouma, Mixed mode fracture of cementitious bimaterial interfaces; part I: experimental results, Eng. Fract. Mech. 60 (1998) 83–94.
[13] J. Červenka, J.M. Chandra Kishen, V.E. Saouma, Mixed mode fracture of cementitious bimaterial interfaces; part II: numerical simulation, Eng. Fract. Mech. 60 (1998) 95–107.
[14] F.J. Alaee, B.L. Karihaloo, Fracture model for flexural failure of beams retrofitted with CARDIFRC, ASCE J. of Eng. Mech. 129 (2003) 1028–1038.
[15] C.K.Y. Leung, Fracture mechanics of debonding failure in FRP-strengthened concrete beams, in: V.C. Li, C.K.Y. Leung, K.J. Willam, S.L. Billington (Eds)., Fracture Mechanics of Concrete and Concrete Structures, 2004, pp. 41–52.
[16] A. Carpinteri, G. Lacidogna, M. Paggi, Acoustic emission monitoring and numerical modeling of FRP delamination in RC beams with non-rectangular cross-section, RILEM Mater. Struct. 40 (2007) 553–566.
[17] fib Bulletin, Design and use of externally bonded FRP reinforcement (FRP EBR) for reinforced concrete structures, Bulletin no. 14, Prepared by sub-group EBR (externally bonded reinforcement) of fib Task Group 9.3 FRP reinforcement for concrete structures, 2001.
[18] T.K. O'Brien, I.L. Paris, Exploratory investigation of failure mechanisms in transition regions between solid laminates and X-cor truss sandwich, Compos. Struct. 57 (2002) 189–204.

[19] P. Négre, D. Steglich, W. Brocks, Crack extension at an interface: prediction of fracture toughness and simulation of crack path deviation, Int. J. Fract. 134 (2005) 209–229.
[20] A. Lammer, Mechanical properties of polycrystalline diamonds, Mater. Sci. Technol. 4 (1988) 949–955.
[21] J. Gurland, New scientific approaches to development of tool materials, Int. Mater. Rev. 33 (1988) 151–166.
[22] K.J. Dunn, M. Lee, The fracture and fatigue of sintered diamond compact, J. Mater. Sci. 14 (1979) 882–890.
[23] M.V. Sneddon, D.R. Hall, Polycrystalline diamond: manufacture, wear mechanisms, and implications for bit design, J. Pet. Technol. 40 (1988) 1593–1601.
[24] E. Viola, A. Piva, Plane strain interfacial fracture analysis of a bimaterial incompressible body, Eng. Fract. Mech. 15 (1981) 131–142.
[25] F. Erdogan, G.C. Sih, On the crack extension in plates under plane loading and transverse shear, J. Basic Eng. 85 (1963) 1–7.
[26] A. Piva, E. Viola, Biaxial load effects on a crack between dissimilar media, Eng. Fract. Mech. 13 (1980) 143–174.
[27] M.-Y. He, J.W. Hutchinson, Crack deflection at an interface between dissimilar elastic materials, Int. J. Solids Struct. 25 (1989) 1053–1067.
[28] G.D. Gupta, Strain energy release rate for mixed mode crack problem, ASME Publication, 76-WA/PVP-7, 1976.
[29] M.-Y. He, A.G. Evans, J.W. Hutchinson, Crack deflection at an interface between dissimilar elastic materials: role of residual stresses, Int. J. Solids Struct. 31 (1994) 3443–3455.
[30] P.A. Wawrzynek, A.R. Ingraffea, Interactive finite element analysis of fracture processes: an integrated approach, Theor. Appl. Fract. Mech. 8 (1987) 137–150.
[31] P.A. Wawrzynek, A.R. Ingraffea, Discrete modeling of crack propagation: theoretical aspects and implementation issues in two and three dimensions, Technical Report 91-5, School of Civil and Environmental Engineering, Cornell University, 1991.
[32] C.H. Wang, Fracture of interface cracks under combined loading, Eng. Fract. Mech. 56 (1997) 77–86.
[33] A. Carpinteri, M. Paggi, Self-similarity and crack growth instability in the correlation between the Paris' constants, Eng. Fract. Mech. 74 (2007) 1041–1053.
[34] A. Carpinteri, Structural Mechanics: a Unified Approach, E&FN Spon, London, 1997.
[35] A. Carpinteri, N. Pugno, Thermal loading in multi-layered and/or functionally graded materials: residual stress field, delamination, fatigue and related size effects, Int. J. Solids Struct. 43 (2006) 828–841.
[36] H.N. Linsbauer, A.R. Ingraffea, H.P. Rossmanith, P.A. Wawrzynek, Simulation of cracking in large arch dam: part I, ASCE J. Struct. Eng. 115 (1989) 1599–1615.
[37] H.N. Linsbauer, A.R. Ingraffea, H.P. Rossmanith, P.A. Wawrzynek, Simulation of cracking in large arch dam: part II, ASCE J. Struct. Eng. 115 (1989) 1616–1630.
[38] A. Carpinteri, M. Paggi, N. Pugno, Numerical evaluation of generalized stress-intensity factors in multi-layered composites, Int. J. Solids Struct. 43 (2006) 627–641.
[39] R.S. Barsoum, On the use of isoparametric finite elements in linear fracture mechanics, Int. J. Numer. Methods Eng. 10 (1976) 25–37.
[40] R.S. Barsoum, Asymptotic fields at interfaces using the finite element iterative method, Comput. Struct. 35 (1990) 285–292.
[41] K.S. Ravichandran, Fracture toughness of two phase WC–Co cermets, Acta Metall. Mater. 42 (1994) 143–150.
[42] A. Carpinteri, Stress-singularity and generalized fracture toughness at the vertex of re-entrant corners, Eng. Fracture Mech. 26 (1987) 143–155.
[43] A. Carpinteri, M. Paggi, Analytical study of the singularities arising at multi-material interfaces in 2D linear elastic problems, Eng. Fracture Mech. 74 (2007) 59–74.
[44] A. Carpinteri, M. Paggi, On the asymptotic stress field in angularly nonhomogeneous materials, Int. J. Fracture 135 (2005) 269–285.
[45] D. Munz, Y.Y. Yang, Stress singularities at the interface in bonded dissimilar materials under mechanical and thermal loading, ASME J. Appl. Mech. 59 (1992) 857–861.