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A DECOUPLED THREE-SCALE APPROACH TO MEMS FAILURE

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SOMMARIO

Nel presente lavoro si affronta lo studio della risposta meccanica di micro sensori MEMS sottoposti ad urti accidentali. Pur essendo state svolte in passato indagini teoriche e numeriche per comprendere le cause di rottura in MEMS a seguito di shock meccanici, una descrizione dettagliata dei meccanismi di rottura nei dispositivi in silicio policristallino risulta ancora parziale. In particolare, appare non sufficientemente indagato il legame tra i fenomeni di rottura micro-meccanici e le onde elastiche che si propagano nel sensore a seguito dell'impatto.

In questo lavoro viene proposto un approccio per le analisi dinamiche di accelerometri MEMS ancorati al *die*. A causa del modesto rapporto tra l'inerzia del sensore e l'inerzia del *die*, viene adottato uno schema multi-scala disaccoppiato: alla macro-scala (*die*) il dispositivo in caduta impatta una superficie rigida e piana; alla meso-scala (sensore) le accelerazioni desunte dalle analisi alla macro-scala sono utilizzate come dati di ingresso per individuare zone critiche del sensore, dove lo stato di sforzo supera una soglia predefinita; alla micro-scala (grano cristallino di silicio) si simula con un approccio coesivo la rottura del MEMS dovuta alla propagazione di fratture inter- e trans-granulari nelle regioni critiche prima individuate.

ABSTRACT

A study of the mechanical response of MEMS sensors subect to accidental drops is dealt with in the present paper. Experimental and theoretical investigations aiming at understanding shock- and drop-induced failures in MEMS sensors were pursued in the past. However, a detailed numerical description of the failure mechanisms in polysilicon devices, and the micro-mechanical links with the stress waves caused by the impact still look incomplete.

In this work, we perform dynamic analyses of MEMS accelerometers supported by a naked die, subect to shock loading due to drops. Due to the small ratio between sensor and die inertial properties, a decoupled three-scale approach is adopted: at the macro-scale (die) it is supposed that the falling device strikes a flat, rigid surface; at the meso-scale (sensor) acceleration records resulting from macro-scale analyses are adopted as input loading to detect critical sensor details; at the micro-scale (silicon grain) crack propagation at grain boundaries and within grains, possibly leading to MEMS failure, is simulated through a cohesive approach.

1. INTRODUCTION

Accidental drop failures are of maor importance in the study of MEMS reliability. Possible drops can occur during transport and mishandling of singled MEMS and also during their service life, while already installed in devices like mobile phones. In such situations, shock waves and the resulting overloads on the sensors can be a cause of failure.

Some recent researches have attacked this problem, showing links between the drop features and the mechanical response of the packaged device [1]-[3]. However, they typically rely on simplified models of the contact conditions between the falling package and the impacted surface (termed target surface henceforth) and of the propagation of shock waves in the package/sensor system. While this approach can quickly furnish results upon calibration, accuracy can get lost in case of very localized failures at sensor level [4].

A simplified multi-scale approach to the analysis of MEMS subect to accidental drop has been recently proposed in [5]-[7]. As a prosecution of the previous work, in the present paper we consider a uni-axial polysilicon MEMS accelerometer supported by a naked die and subect to an accidental drop from a fixed height. We propose a decoupled three-scale numerical scheme to investigate the links between drop height and impact angles (here defined as the Euler angles between the target surface and the bottom surface of the die) and the stress state induced in the sensor. A simulation of fracture processes arising at the end sections of the suspension springs is performed by means of a cohesive approach for a virtual polycrystal [8], similar to the one adopted e.g. in [9],[10].

The proposed approach can be straightforwardly extended to fully packaged sensors by simply changing the geometry of the falling body.

2. MULTI-SCALE ANALYSIS

Inertial MEMS sensors are usually characterized by a very small ratio between the inertia of the sensor itself and the inertia and of the die-cap assembly or of the whole package, independently of the shock suffered by the device. Henceforth by device we mean the assembly of the die-cap and of the sensor.

The dynamics of the device is therefore marginally affected by the presence of the MEMS. This feature justifies the adoption of a decoupled three-scale approach to failure analysis of polysilicon sensors.

At the macro-scale, the whole device is modelled as an elastic isotropic body falling and bouncing off the target surface (which represents the ground when drops are simulated). The simulations at this scale allow for the study of the influence on the acceleration history at the sensor anchor(s) of various factors: geometry of the device; mechanical properties of the device and of the target surface; drop height; device tilting.

At the meso-scale, the MEMS is modelled as a transversely isotropic film. The acceleration records obtained at the macro-scale are adopted as ground motion histories in dynamic simulations. Critical sensor details, where the stress state exceeds a pre-defined bound on the polysilicon carrying capacity, can then be identified.

At the micro-scale, the above mentioned critical MEMS details are modelled as a polycrystalline material, accounting for a representative crystal structure of the polysilicon. Failure, typically linked to intergranular/transgranular dynamic crack growth, is simulated via a cohesive approach to quasi-brittle fracture.

The following hypotheses are adopted in order to configure a worst-case scenario: the target surface is rigid and flat; air viscosity, which decreases the velocity of the device when it strikes the ground, is neglected; the contact between the device and the target surface is frictionless; fluid-structure interaction at the sensor level, leading to viscous damping, is neglected. The above assumptions lead to an overestimation of the stress state in the sensor.

It is worth pointing out that analyses at the micro-scale are here conducted in a deterministic framework. Hence, it is assumed that the adopted crystal structure is representative as for the material response and that a reference value for tensile strength can be used deterministically, to model possible failure mechanisms at the sensor level. It is well know that, at this length-scale, Monte Carlo approaches [10] should be considered to obtain accurate, stochastic outcomes. Alternatively, the Weibull approach for the assessment of brittle materials mechanical strength could be used [11]. In this work the assumed tensile strength reference value corresponds to a failure probability of 63.2% for the material obtained by the productive process, loaded in uniaxial tensile tests.

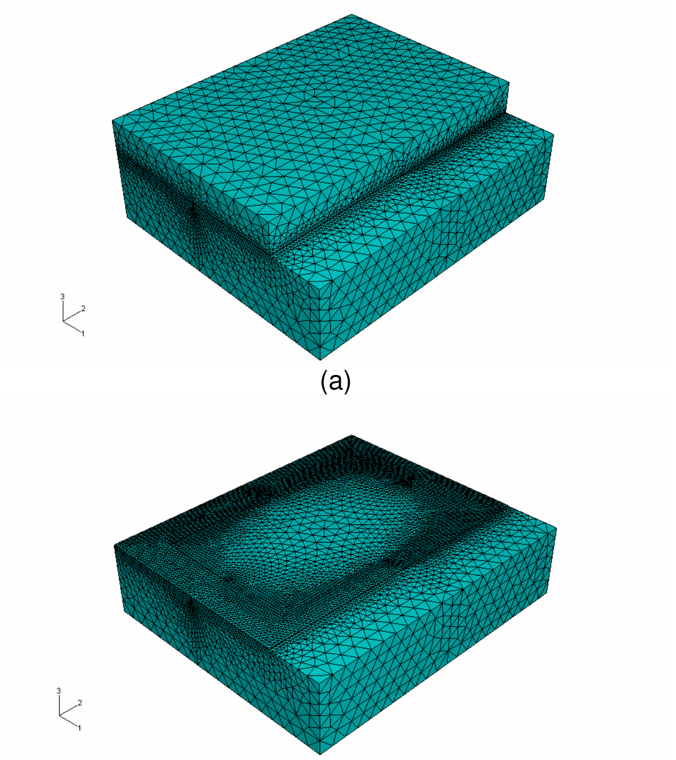
2.1. Macro-scale analysis

After a frictionless impact against a flat surface, the falling die repeatedly bounces. At this length-scale we are interested in the propagation of shock-waves in the bulk of the falling die-cap assembly. Therefore, three-dimensional explicit dynamic simulations are run to model the response of the whole body after the impact.

The geometry of the modelled device is shown in Fig. 1: a space discretization consisting of about 145,000 tetrahedral, four-node linear elements and about 30,000 nodes has been adopted. To obtain a high resolution in the proximity of the anchor point, smaller elements with a characteristic size $l = 30\ \mu\mathrm{m}$ have been used on the top surface of the die.

Both die and cap are made of single-crystal silicon, assumed isotropic for simplicity, featuring Young's modulus $130\ \mathrm{GPa}$, Poisson's ratio 0.22 and mass density $\rho_s = 2330\ \mathrm{Kg/m^3}$. Drop height is assigned as h=$150\ \mathrm{cm}$. Because of the asymmetric position of the cap with respect to the die center of gravity (see Fig. 1), it is expected that while falling the die-cap assembly rotates around axis x_2.

As an example of results, in Fig. 2, lateral views of the device bouncing after the impact with a rigid target surface are shown. Because of the asymmetric geometry of the die-cap assembly, rigid body rotations show up in the late stage of device response, that is for time $t > 50$ μs.



(a)

(b)

Fig. 1 - Macro-scale analyses (die/cap length-scale). (a) The die-cap mesh; (b) the die mesh only

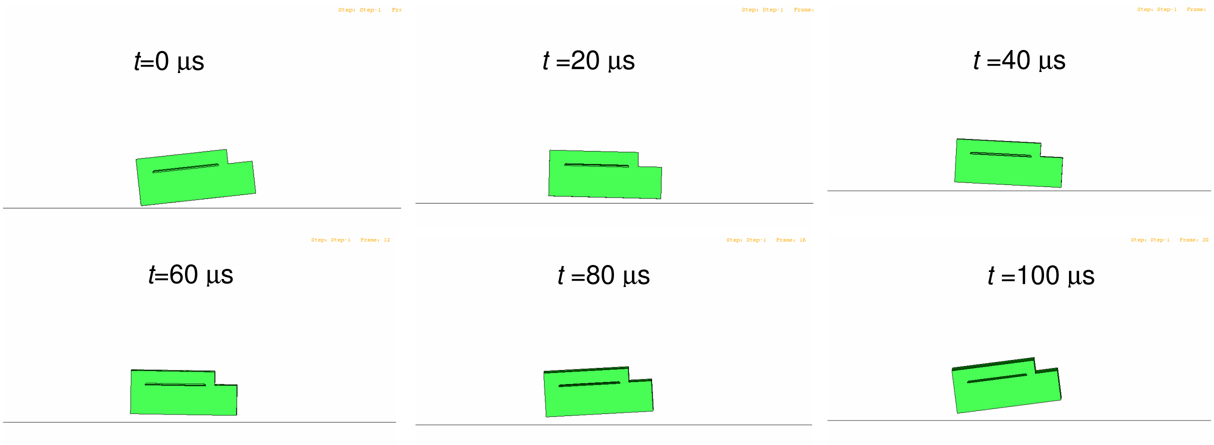


Fig. 2 - Drop height 150 cm; impact angle 10°.
Snapshots of the bouncing die, taken every 20 μs after the impact

In cases of small impact angles (within the range 5°-20°, measured around axis x_2), the die experiences repeated collisions with the target surface at opposite edges of the bottom die surface.

Possible interactions between the shock waves emanating from the impact locations can take place inside the die; we then conducted all the analyses up to $t_{end} = 100$ μs, which seems a reasonable bound on the time interval to be scanned to detect peak stress states in the sensor at the meso-scale.

During the analyses, the acceleration at the sensor anchor is continuously monitored. Because rigid body-like motions of the assembly show up for $t > 50$ μs, also the rotational accelerations at the sensor anchor are stored.

Fig. 3 shows the acceleration records (scaled by the gravity acceleration g) in the local sensing direction z, orthogonal to the substrate, ust after the impac t, namely for $0 < t < 2$ μs. The results relevant to the top, bottom and some tilted impact cases are compared.

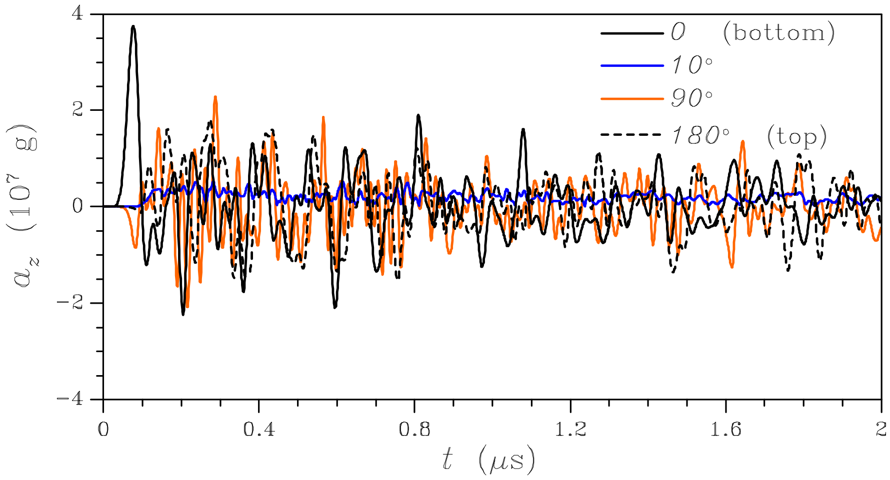


Fig. 3 – Effects of the impact angle on the acceleration at the sensor anchor, $0 < t < 2$ μs.

Due to the multiple reflections of shock-waves at the free surfaces of the body, even in this very small period of time the acceleration histories show sudden variations, characterized by a large amount of peaks. From Fig. 3 it can be also noticed that tilting affects the acceleration records by reducing peak values.

2.2. Meso-scale analysis

At this length-scale the dynamic response of the uni-axial MEMS accelerometer shown in Fig. 4 and placed in the die cavity is analyzed. Specifically, we aim at detecting where the stress state caused by the impact exceeds or even approaches a pre-defined bound on the actual strength of the polysilicon.

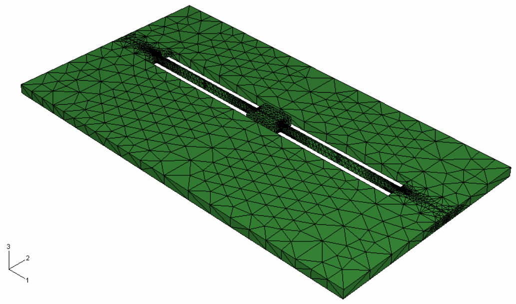


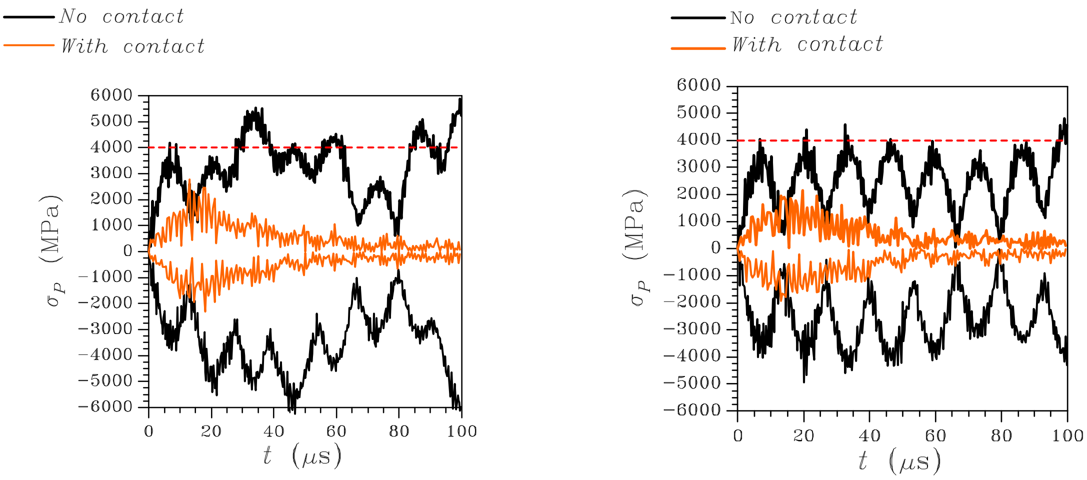
Fig. 4 - Meso-scale analyses (sensor length-scale). View of the sensor mesh

The sensor is constituted by a seismic plate, connected via two slender beams to the anchor point. Both the seismic plate and the beams are made of poly-crystal silicon, assumed as a transversally isotropic material with the texture direction aligned with axis x_3. The following parameters are used: E_1= E_2 = 162.70 GPa, ν_{12}=0.2225, ν_{13}=ν_{23}= 0.280, E_3=130.13 GPa, G_{13}=G_{23}=79.6 GPa. In order to account for the perforated bulk of the seismic plate, reduced mechanical and mass properties are adopted for the polysilicon in there.

Two approaches are here compared: first, possible interactions of the movable parts of the sensor (plate and beams) with stoppers and with surfaces of the cavity inside the die/cap assembly are disregarded; second, contact with stoppers and with surfaces of the cavity is allowed.

Outcomes of the simulations, not reported here for brevity, clearly show that the bending vibrations of the plate are negligible. On the other hand the beams, because of their smaller stiffness, are subject to bending as well as torsional vibrations. The details which are likely to fail after the impact are therefore the beam-anchor and the beam-plate joint sections of both beams.

The presence of re-entrant corners cause stress concentration, which requires a detailed space discretization. As for the joint sections, Fig. 5 collects the envelopes of the principal stresses up to t_{end} =100 μs caused by a bottom impact: both the results obtained by accounting for the interaction with die and stoppers and by disregarding them are here shown for comparison purposes. A red dashed line stands for the reference tensile strength, as discussed in Section 2.



(a) (b)

Fig. 5 - Drop height 150 cm; impact angle 0° (bottom case).
Principal stress envelopes at beam end-sections (a) towards anchor and (b) towards plate.

When contact is disregarded, it can be noticed that low frequency variations, with period T_{low}=13 μs, are superposed to higher frequency ones. These latter ones are linked to higher bending and torsional vibration modes of the beams. The top case (here not reported) appears more critical than the bottom one when contact is allowed. The reason of this behavior is related to the overall deflection permitted to the beams towards the die floor and towards the die cap (i.e. in the direction normal to the plate). The displacement of the beams before a contact occurs is greater in the top case than in the bottom case.

In both the cases, since the displacement is imposed at the anchor, at the real beginning only the beam region near the anchor is moved towards the cap; it is only after a certain delay that the bulk plate mass follows the movement, while the beams oscillate, both with bending and torsional modes. This behavior repeats itself also during the remaining analysis time. The stress in the structure remains rather low, except for the beam ends where stress concentration is evidenced. This local evolution is responsible of the possible device failure.

2.3. Micro-scale analysis

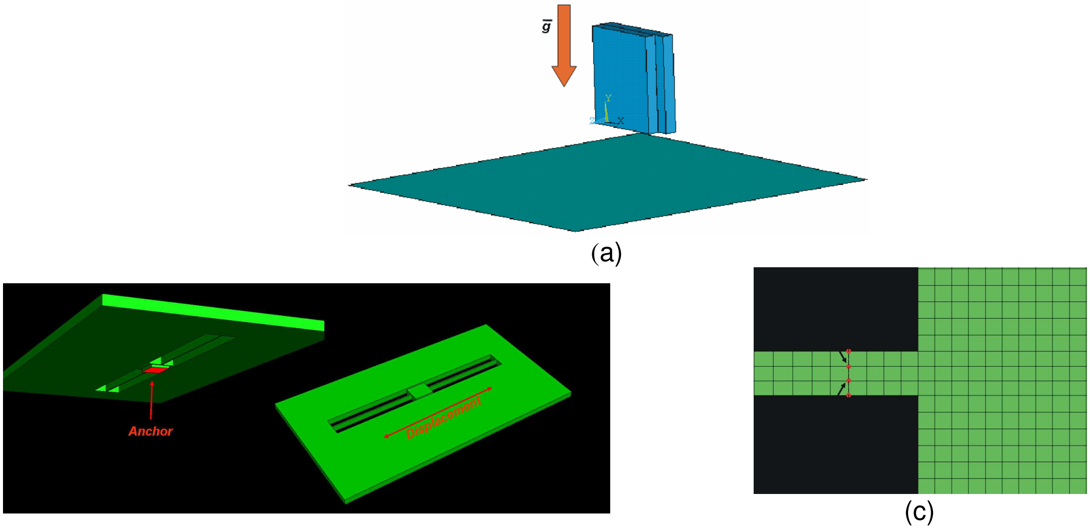
In order to verify the resistance of the device in correspondence of the connection of the suspension spring to the anchor, micro-scale simulations are performed allowing for crack initiation and propagation in a virtual polycrystal (see [5]-[8] for details). The fracture process in the polycrystal is simulated: (a) by making use of a numerical Voronoi tessellation for the description of the granular microstructure ([9],[10]); (b) by adopting cohesive softening interfaces automatically plugged-in as soon as a critical stress criterion is satisfied.

An initial device orientation like the one shown in Fig. 6, i.e. obtained by a rotation of 90° about the x_2 axis, is considered to get a meaningful bidimensional problem. In Fig. 6, also the direction of induced displacement in the sensor, along the beam axis, is shown. The tessellation of the anchor-beam detail analyzed is shown in Fig. 7, together with the used mesh (made of about 7,500 six-node triangular elements).

Each crystal is randomly oriented, and its elastic properties are assigned in a local reference frame [12],[13]. The mechanical response of the cohesive surfaces is governed by a Camacho-Ortiz-like linear softening law [14].

Two simulations are carried out by adopting two different strength properties for the inter-granular and trans-granular surfaces, even if both characterized by a common fracture energy equal to 7 N/m. In the first simulation (Material I) it is assumed that the strength properties within grains and at grain boundaries are the same (σ_{tmax} = 2.0 GPa); in the second simulation (Material II) the stress-carrying capacity of grain boundaries is assumed lower than inside grains (respectively, σ_{tmax}=1.5 GPa and σ_{tmax}=2.0 GPa).

On the side marked in black in the Fig. 7(a) the evolution of relative displacement w.r.t. the anchor computed in the meso-scale simulation at the points indicated in Fig. 6(c) is imposed. The other side is restrained. The two simulations show that the shock causes a failure of the device, due to percolation of a main crack, in about 13.5 μs. The crack evolution is displayed in Fig. 8 for the analysis carried out with both Materials I and II.

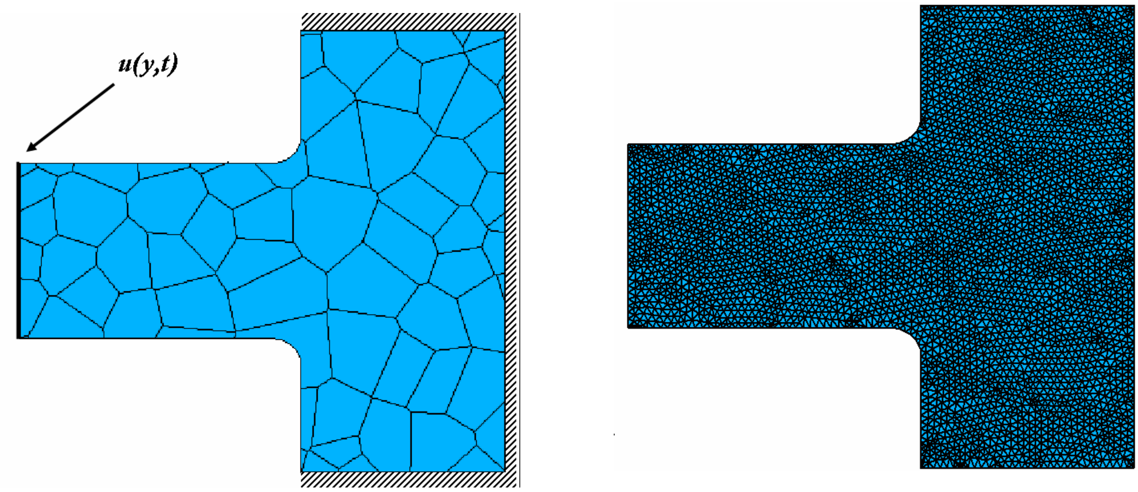


(a)

(c)

(b)

Fig. 6 - Configuration adopted for the decoupled approach. (a) die drop orientation; (b) displacement induced in the sensor plane; (c) detail of the anchor for 2D micro-scale analysis.



(a)

(b)

Fig. 7 - (a) Microstructural morphology and (b) mesh of the detail.

From Fig. 8 it is possible to notice that the crack path is initially the same and trans-granular for the two cases analyzed. Once the crack length reaches almost one half of the section length, in the case analyzed with Material I (same properties on grain and grain boundary), it continues to grow along the trans-granular surfaces, whereas in the other case, it kinks on the grain boundary to terminate the propagation again trans-granularly. In both cases the two paths are very similar and even the time evolution of the crack length can hardly be distinguished.
It is worth emphasizing that a more precise shock assessment should require a relatively high number of simulations performed on nominally identical specimens, in order to take into account the effect of the random orientation of the grains and of the different possible micro-structural morphologies.

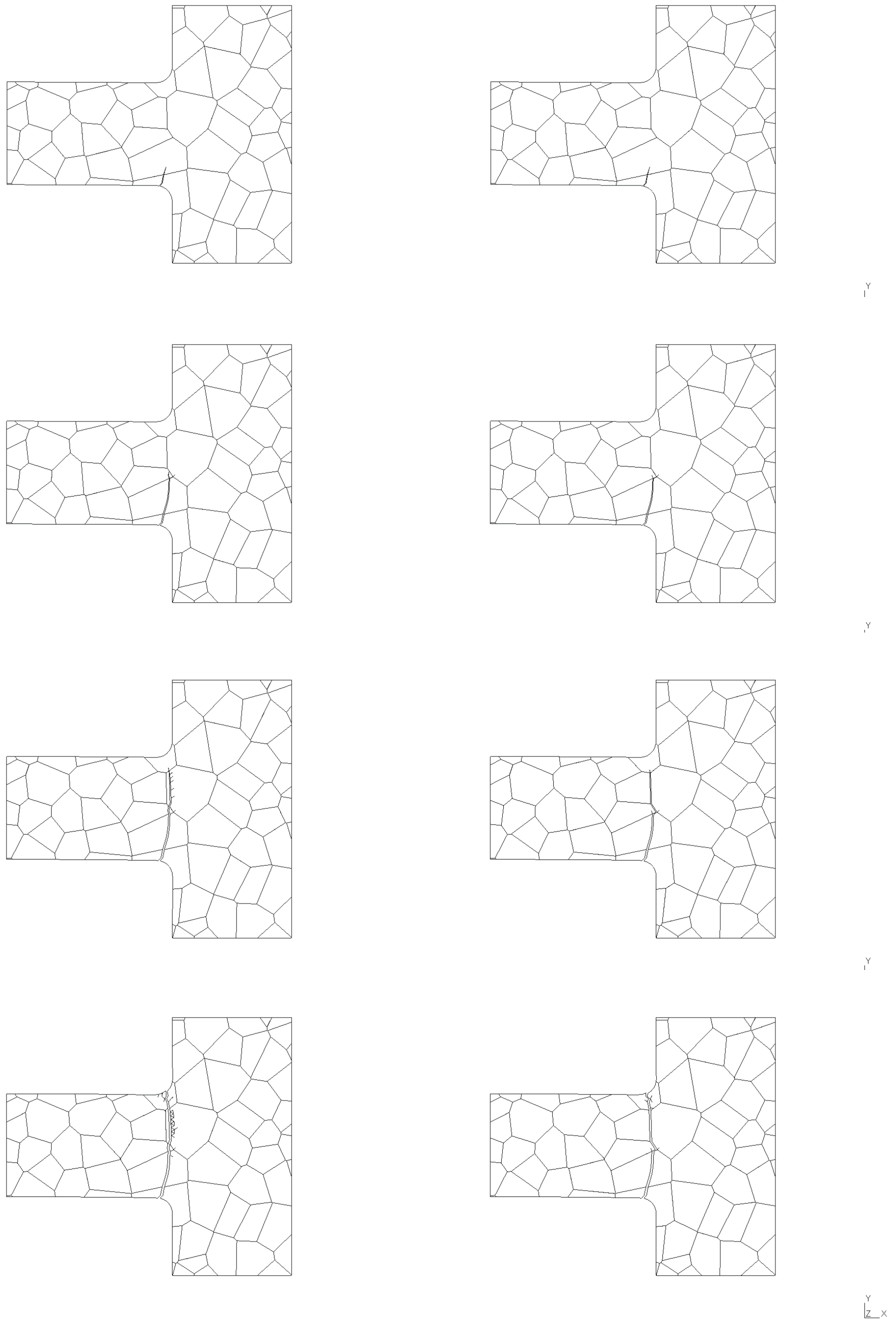


Fig. 8 - Dynamic crack path evolution for Material I (left) and Material II (right)

3. CONCLUSIONS

A simplified, decoupled three-scale approach to the analysis of drop-induced failure of polysilicon MEMS sensors has been proposed. Displacement histories taken from a higher scale analysis are used as input at the lower scales. This procedure is able to identify critical regions in MEMS, where high stress concentration can lead to failure. It is shown that, depending on the failure mechanism in the sensor, the maximum acceleration peak observed at the macro-scale cannot be considered as an effective parameter to assess the safety of the device. In fact, the sensor beams are subected to a flexural/torsional stress state, affected also by the interaction with the stoppers and with the walls of the cavity where the accelerometer is placed.

An example of crack growth simulation at the micro-scale for a reference two-dimensional model, meaningful for the considered device, shows the promising capabilities of the offered approach.

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REFERENCES

[1] Srikar V T, Senturia S D. The reliability of microelectromechanical systems (MEMS) in shock environments. J. of Microelectromechanical Systems. 2002, 11:206-214.
[2] Li G S, Shemansky F A. Drop test and analysis on micro-machined structures. Sensors and Actuators A. 2000, 85:280-286.
[3] Shan, H, Su J, hu J, u L. Three-Dimensional Modeling and Simulation of a Falling Electronic Device. Journal of Computational and Nonlinear Dynamics. 2007, 2:22–31.
[4] Suhir E. Is the maximum acceleration an adequate criterion of the dynamic strength of a structural element in an electronic product IEEE Transactions on Components, Packaging and Manifacturing Technology. 1997, 20:513–517.
[5] Corigliano A, Cacchione F, Frangi A, erbini S. Simulation of impact rupture in polysilicon MEMS. In Proceedings of Eurosime06. 2006, Como, April 24-26.
[6] Corigliano A, Cacchione F, Frangi A, erbini S. Micro-scale simulation of impact rupture in polysilicon MEMS. In Proceedings of ECF16. 2006, Alexandropoulos, July 3-7.
[7] Ghisi A, Fachin F, Mariani S, Corigliano A, erbini S. Multi-scale modeling of shock-induced failure of polysilicon MEMS. In Proceedings of Eurosime07. 2007, London, April 16-18.
[8] Cacchione F, Corigliano A, erbini S. Parametric study of fracture properties in polycrystalline MEMS. In Proceedings of Eurosime07. 2007, London, April 16-18.
[9] Espinosa H, avattieri P. A grain level model for the study of failure initiation and evolution in polycrystalline brittle materials. Part I: theory and numerical implementation. Mechanics of Materials. 2003, 35:333–364.
[10] Mullen R L, Ballarini R, in , Heuer H. Monte Carlo simulation of effective elastic constants of polycristalline thin films. Acta Mater. 1997, 45:2247–2255.
[11] Weibull W. A statistical distribution of wide applicability. J. Appl. Mech. 1951, 18:293–297.
[12] Brantley W A. Calculated elastic constants for stress problems associated with semiconductor devices. J. Appl. Phys. 1973, 44:534–535.
[13] Nye J F. Physical properties of crystals. Clarendon, Oxford, 1985.
[14] Camacho G T, Ortiz M. Computational Modelling of Impact Damage in Brittle Materials. Int. J. of Solid Structures. 1996, 33: 2899-2938.