Crack propagation within Penrose tilling-based structures

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Abstract. During the past few years, there has been a growing interest for novel materials with architectured structures. While they provide promising properties for high performance engineering applications they induce new scientific challenges by considerably increasing the mechanical space design on both the material and morphological side. Particularly, quasi-periodic structures have demonstrated unique properties regarding various physical phenomena (e.g. energy storage in local non-propagative vibration modes or enhanced resistance to the propagation of defects [1,2]) which open a number of opportunities in the field of fracture mechanics. In that context, we investigate in the present work the impact of Penrose tilling-based lattice structure on the quasi-static crack propagation, bifurcation and branching within PMMA specimens. The latter are subjected to DCB tests and a dedicated beam-based DIC strategy is used to capture the local kinematics, especially bending modes. Results are compared with lattice simulations allowing for the estimation of the effective local propagation conditions.

Introduction

While the effective elastic properties and energy absorption capabilities of lattice structures under compression have been widely studied their failure resistance remains unexplored. Contrary to continuous media, lattice structures embed additional degrees of freedom. Local lattice rotations play a major role in the appearance of mechanical instabilities such as buckling then cracking and thus need to be accurately captured as well as the discrete nature of the kinematic fields. Since standard FE-based DIC strategy, based on continuum framework, is not totally satisfactory to address this problem the key consists therefore in introducing an Integrated DIC framework, based on beam theory. The later allow for a direct comparison with results output, for instance, from lattice simulations leading eventually to an accurate estimation of the local mechanical loading conditions accompanying the failure event. In the following, 2D Penrose tiling-based structures are investigated.

Sample preparation and test conditions

Double Cantilever Beam (DCB) specimen geometries are manufactured into 300 mm x 160 mm x 6 mm transparent PMMA plates. Penrose tiling patterns (see Fig. 1) are then produced through laser cut technique and a 0.3 mm thick, approximatively 5 cells long pre-crack is introduced. Different aspect ratios are considered, 5 and 10 (not presented here) meaning a beam thickness of 1 and 0.5 mm respectively for a beam length of 5 mm. Optical contrast is obtained by covering samples with both a uniform layer of black paint and a white speckle-like pattern. The sample is clamped on one end within the tensile test machine crosshead while on the other end the clamped wedge is moved into the sample at a constant speed of 0.6 mm/min producing stable crack growth. Finally, pictures of the deforming specimen are taken every 5s with a spatial resolution of 19 Mpx.

Beam-based DIC

Displacement fields are obtained from a multi-step approach. First, continuous displacement fields are obtained from standard DIC, on a regular mesh made of 100 x 100 pixels Q4P1 elements. The later provides a relevant initiation for the identification of the local effective structure motion. Fields are then interpolated at nodes of an image-based lattice mesh. Rotations are set to zero, and IDIC strategy is applied. Beam motion is defined by 3 degree of freedom, i.e. the curvilinear axial and transverse displacements and a rotation, as follows:

$$\overrightarrow{d(l)} = \begin{pmatrix} u(l) \\ v(l) \end{pmatrix} = \begin{Bmatrix} u_1 P_1(l) + \ u_2 P_2(l) \\ v_1 P_3(l) + v_2 P_4(l) + \theta_1 P_5(l) + \theta_2 P_6(l) \end{Bmatrix} \tag{1}$$

with shape functions P_i verifying $u(0) = u_1,\ u(L) = u_2,\ \frac{\partial v(l)}{l} = \theta(l),\ \theta(0) = \theta_1,\ \theta(L) = \theta_2$, and L the beam length. Finally, the problem consists in solving the optical flow equation given the prescribed form for u and v. The dataset is finally completed with lattice simulations on identical structures. In the latter, homogeneous and symmetrical transverse displacement is imposed on front nodes located on both side of the pre-crack, the top part is clamped and a maximum strain energy criterion is used to identify, then iteratively removing cracked beam.

Experiments

Fig1 presents kinematic fields obtained on one of the specimen (aspect ratio is 5) as well as images of the specimen at rest and deformed. Fig1-b shows that the crack growth is significantly affected by the structure even if the main path remains almost straight. Indeed, the crack systematically turns around the

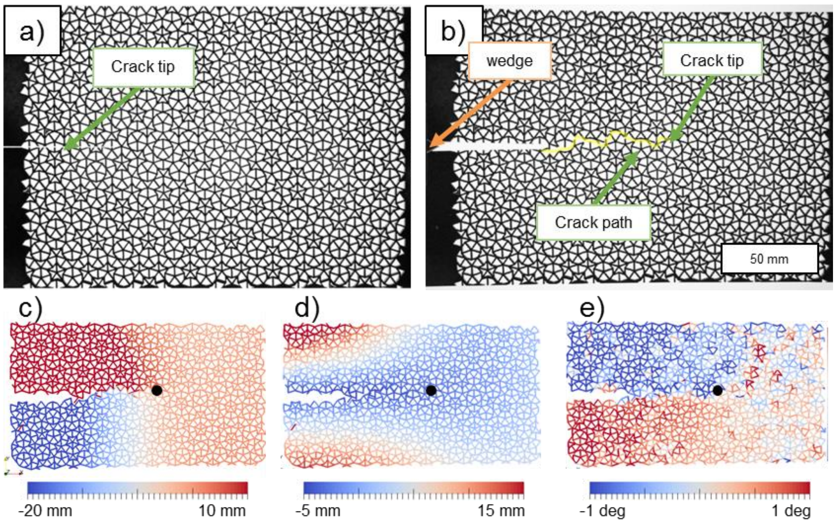

Figure 1: Fracture tests on Penrose tiling-based PMMA specimens. (a) Image at rest, (b) loaded state, (c) and (d) the measured transverse and axial displacement fields and (e) the rotation field.

smallest wheels, i.e. skirting the strong (5th beam) star-like junctions. This point is also observed on lattice simulations (see Fig2-a) confirming the strength of such junctions. Fig1-c to e evidence the ability of the beam-based DIC strategy to capture the local kinematics as well as the singularity induced by the crack all along the quasi-static propagation. Rotations from -1 to 1° are observed while a clear moment is visible downstream from the crack tip suggesting a further bifurcation of the crack. A similar scenario, but on the opposite side, is observed on the simulated rotation field (see Fig2-b). Nevertheless, due to the buckling of the structure, the test has been stopped before the appearance of such a bifurcation. It is important to notice that the bifurcation and branching are significantly affected by the boundary conditions which are idealized in the present study whereas the Fig1-a evidences a clear experimental dissymmetry. Applying measured displacements could probably lead to more predictive results. The discrepancy is here visible very early when in the simulation the first wheel is skirted by the top whereas in the experiment it is done by the bottom.

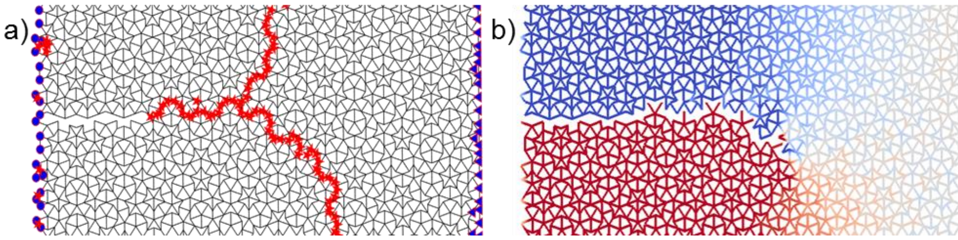

Figure 2: Lattice simulations. a) crack path and b) iso-contour of the rotation field

Conclusion

Such preliminary results validate the metrological procedure. Complementary tests are currently done using the TDCB configuration (to avoid buckling) and the influence of the different beam aspect ratio is investigated. It is also attended in a near future to address the dynamic problem using ultra-high-speed imaging, especially the appearance of the band-gap phenomenon, which could strongly affect the crack propagation even potentially limit it.

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