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1 **Failure mechanisms of plasterboard in nail pull**
2 **test determined by X-ray microtomography and**
3 **digital volume correlation**

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14 **Abstract**

15 To design lightweight plasterboard and optimize the compromise between ther-
16 mal resistance and mechanical strength, it is important to characterize its
17 strength as characterized with the normative “Nail pull” test. Understanding
18 the phenomenology of this test is the key to identifying the limiting factor in
19 terms of load carrying capacity. In this work, the degradation mechanisms of
20 lightweight plasterboard are analyzed via tests conducted in-situ in a labo-
21 ratory tomograph. Through the analysis of the kinematics by digital volume
22 correlation, the different mechanisms at play up to failure mechanism have
23 been identified, i.e., quasi-elastic regime, failure of the roller coating layer,
24 core compaction and core failure. The compaction of the core by the collapse

25 of porosity in compression is recognized as the limiting factor in terms of
26 compressive strength and tearing resistance.

27 *Keywords:* Digital volume correlation, lightweight plasterboard, nail pull test,
28 X-ray tomography

29 **1 Introduction**

30 Gypsum boards are sandwiches composed of a core of plaster cast between
31 two paper layers. They are finishing products very commonly used in con-
32 struction. Gypsum is a material particularly suited to indoor use due to its
33 thermal and acoustic insulation properties in addition to its fire resistance.
34 The social demand for reducing the carbon footprint and energy consumption
35 of plasterboard manufacturing is a strong motivation for innovation. Lighten-
36 ing the material through the incorporation of foam in the stucco slurry is thus
37 a natural trend. It requires a good control of the chemical formulation and
38 additives, the setting conditions and the overall industrial processes so as to
39 preserve the performance level on all required properties.

40 In addition to its fire resistance, lightweight plasterboard must meet mechan-
41 ical requirements [1]. The *flexural strength* is essential for the transport, han-
42 dling and installation of the board. *Hardness* characterizes the ability to pre-
43 serve the surface geometric integrity after shocks and contacts. The third and
44 last property that is considered is the *nail pull strength* or *tear resistance*.
45 This quantity defines the ability of the board to be nailed or screwed. This
46 third property is the most severe to meet for light plasterboards. The nail pull
47 resistance remains the essential condition that prevents a significant decrease
48 in surface density of plasterboard beyond the current level ranging from 7.2 to

49 8.2 kg/m² for 12.7 mm-thick plates [2,3]. This constitutes a strong motivation
50 for understanding the physical phenomena at play in the damage and failure
51 mechanism of the nail pull test. The final aim for industry is to optimize the
52 stucco microstructure, the foam characteristics or the fabrication process to
53 address the relevant features to enhance the mechanical properties.

54 The American standard ASTM C473 [1] describes the conventional methods
55 for physical testing of gypsum boards. The nail pull test aims at quantifying
56 the perforation resistance of gypsum board with a nail head. The diameter of
57 the nail is equal to 2.515 ± 0.076 mm and that of the head is 6.35 ± 0.127 mm.
58 Two methods of perforation are described. The first is carried out by hand,
59 with a lever arm, considered to be with constant force. The second is conducted
60 on a tension/compression testing machine with constant speed of the nail (i.e.
61 25 mm/min). The value given for the nail pull resistance is the maximum load
62 when the head of the nail penetrates through plasterboard. According to the
63 ASTM C1396 standard [4], a minimum load level of 350 N has to be reached
64 for 12.7-mm thick plates.

65 The mechanical behavior of plasterboard in nail pull tests is still de-
66 bated [5,3,6–8]. If some phenomena are usually reported (e.g. top paper surface
67 perforation, plaster foam crushing, cone and radial cracking) their sequential
68 or simultaneous character and how they relate to the load/penetration curve
69 are difficult to assess. In most of the reported studies, the mechanism of failure
70 is deduced from the analysis of the macroscopic response curve and also from
71 post-mortem or interrupted test analyses of the specimen that are delicate.
72 The interplay of the different phenomena remains to be elucidated precisely.

73 X-ray computed tomography (X-CT) is valuable for the 3D inspection of ma-
74 terial microstructures (especially for porous media) in a non-destructive and

75 non-intrusive way [15–17,9]. It therefore constitutes a unique opportunity to
76 have an exhaustive characterization of the different stages of damage and fail-
77 ure controlling the nail pull strength. However, a number of acquisitions are
78 required through a test and, ideally, such tests are performed *in-situ*. This is
79 precisely the objective of the present study.

80 One key improvement provided by computed tomography is that the *same*
81 sample can be imaged in the bulk at different levels of load. For some materials
82 (e.g. sand), the fact that the sample is unloaded to be imaged *ex-situ* does not
83 significantly change the sought information (i.e. density maps [18]) provided
84 the hydrostatic confinement is still applied. Tomodensitometric measurements
85 allowed Desrues et al. [19] to study the complex pattern of localization bands in
86 the bulk of sand samples. The development of *in-situ* mechanical experiments
87 coupled with X-ray tomography began with the observations of crack openings
88 in aluminum alloy [20]. Mechanical tests coupled with *in-situ* tomographic
89 observations have subsequently been developed [21–23]. Significant progress
90 has been made in the design of new testing setups and more importantly
91 on the understanding of various degradation mechanisms that could only be
92 revealed thanks to observations in the bulk of materials.

93 Reconstructed X-ray tomography volumes can be quantitatively analyzed via
94 Digital Volume Correlation (DVC) [21,24,26–30] to measure the displacement
95 fields in the bulk of samples. DVC is the 3D extension of digital image correla-
96 tion [25] whereby displacement fields are measured by registering sub-volumes
97 in the deformed configuration with those in the reference configuration. Be-
98 ing based on 3D gray level valued images, DVC provides three dimensional
99 displacement fields. Global approaches in which the displacement field is inter-
100 polated via finite element discretizations have been introduced later on [31].

101 In the following study, a regularized approach will be utilized [35,36].

102 After a detailed description of the experimental procedure used herein, the
103 failure mechanisms of lightweight plasterboard are discussed by comparing
104 the load-displacement curve recorded during the test and the in-situ tomo-
105 graphic observations. In addition, Digital Volume Correlation (DVC) is used
106 to measure the three dimensional displacement field all along the test.

107 **2 Experimental study**

108 *2.1 Studied material*

109 The studied material is lightweight plasterboard mainly composed of a foamed
110 plaster core surfaced with two paper linings. The main function of the two pa-
111 per layers is to carry the tensile stresses and to protect the sandwich core. The
112 foamed core mainly contributes to the rigidity of the board and to bear shear
113 loadings. It also provides the compressive strength. At the interface between
114 the paper facing and the core plaster foam, a thin layer of dense gypsum (i.e.
115 unfoamed plaster) referred to as “roller coating” is introduced at the fabrica-
116 tion stage to provide an enhanced hardness as well as tensile/flexural strength.
117 Adhesion between the paper and the gypsum core is promoted by the addi-
118 tion of starch. The latter has definite advantages over other binders, such as
119 epoxy and phenolic components, in construction applications, as it is readily
120 available, environmentally friendly, inexpensive and renewable.

121 Figure 1 shows a slice through a tomographic image volume that reveals the
122 different components of lightweight plasterboard.

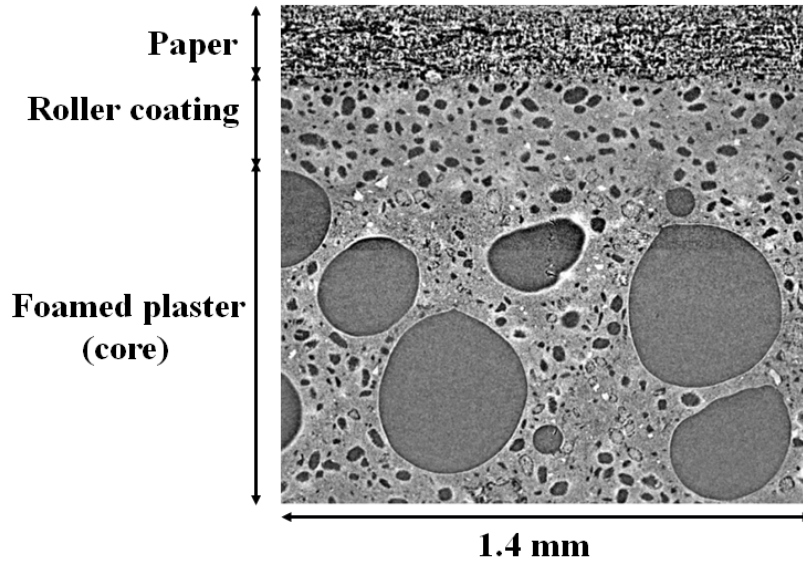


Fig. 1. Main components of lightweight plasterboard revealed thanks to a microtomographic section

123 This scan was acquired at beamline ID19 of the European Synchrotron Radia-
 124 tion Facility (ESRF, Grenoble, France) at a resolution of 1.4 μm . The studied
 125 plasterboard has a very high pore volume fraction (about 75%). The higher
 126 density of the roller coating layer is easily recognized. The microstructure of
 127 the foam is complex and multi-scale. Well-formed, round pores issued from the
 128 foam incorporation are observed with diameters ranging from 200 to 500 μm .
 129 Their surface consists of gypsum micro-crystals lying parallel to the surface.
 130 The individual gypsum crystals are acicular. Their size is about 0.4 μm in
 131 width and 5 μm in length. They appear entangled yet they leave a significant
 132 internal porosity with pore size comparable to that of the micro-crystals.

133 Figure 2 shows SEM observations of the studied material. As can be seen in
 134 Figure 2(a), the material shows a broad range of bubble size, yet most are rel-
 135 atively large (i.e. few hundredths of micrometers), round shaped, well-spaced
 136 and rarely interconnected. Figure 2(b) shows that, in addition to the bubbles
 137 that have smooth boundaries, smaller pores formed during the setting. A late

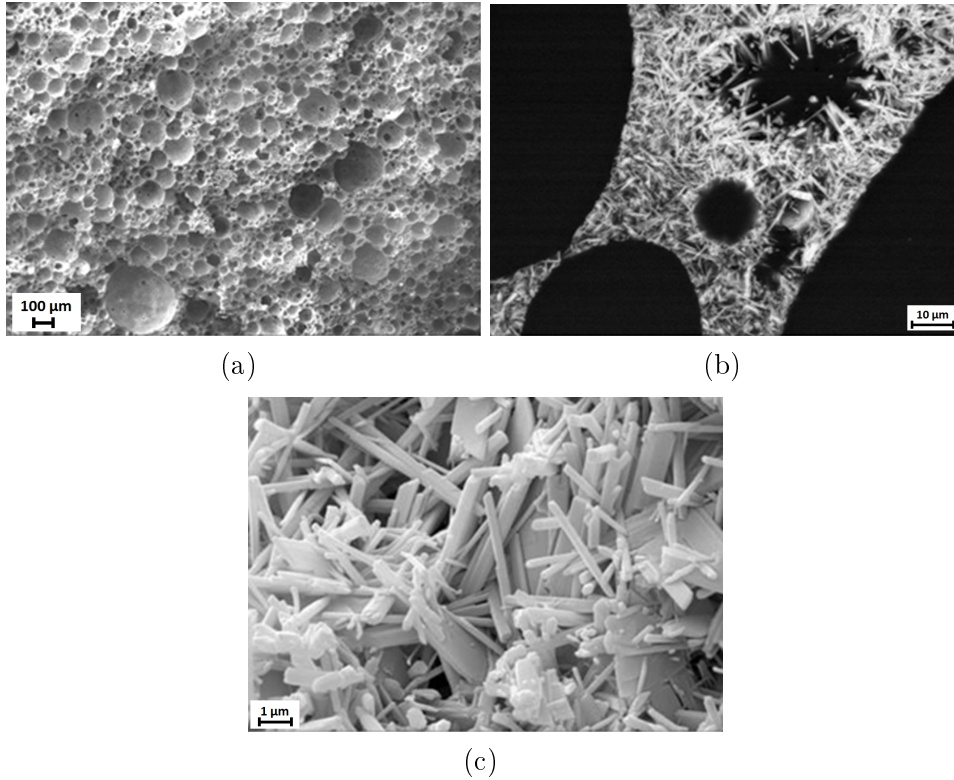


Fig. 2. SEM pictures of foamed gypsum at different magnifications

138 dissolution and crystallization give rise to a very spiky boundary. At an even
 139 smaller scale (Figure 2(c)), gypsum crystals are seen to be distributed ho-
 140 mogeneously, without preferential direction, presenting typical entanglements
 141 that are known to improve the cohesion and resistance of plaster [14].

142 2.2 *In-situ* nail pull test

143 Understanding the failure mechanisms in nail pull tests requires observations
 144 in the bulk of the material to be performed since no direct information is
 145 available on the external surfaces of samples. This is possible by resorting to
 146 X-ray computed tomography [16,17,9]. This technique is particularly appealing
 147 in the present case since the material is very heterogeneous (Figure 1). Further,
 148 these analyses can even be more informative when *in-situ* mechanical tests are

149 performed during which 3D X-ray tomography scans are acquired at different
150 stages of loading [23].

151 In the present study, a new setup has been designed to perform *in-situ* nail
152 pull tests within a laboratory X-ray tomograph. The experiment has been
153 conducted on a Phoenix V Tome X[®] tomograph, using a source setting of
154 90 KV, 220 μ A and a 1920×1536 pixel flat panel detector (see Ref. [23]
155 for more details). The physical size of one voxel is 25 μ m, which is a good
156 compromise between the thickness of the tested sample (i.e. 13 mm) and the
157 microstructural features of the material (Figure 1). One thousand radiographs
158 are acquired over a 360° rotation of the tomographic stage for each acquisition.
159 The total acquisition time is 60 minutes. A filtered back-projection algorithm
160 enables 3D volumes to be reconstructed [11,12].

161 The sample used in the reported experiment is prepared from industrial plas-
162 terboard plates. The specimen is a cylinder 50 mm in diameter and 13 mm
163 in height. A hole 2.5 mm in diameter is subsequently drilled along its cen-
164 tral axis (Figure 3(a)). The sample is then put within the nail pull assembly
165 (Figure 3(b)) made of polymethyl methacrylate (PMMA), which is virtually
166 transparent to X-rays. The nail is made of polyether ether ketone (PEEK),
167 which is a semicrystalline thermoplastic with excellent mechanical properties
168 and has also a low X-ray absorption. The sample is supported over an area of
169 5 mm around the perimeter of the assembly. Note that the specimen diame-
170 ter is smaller than specified in the standardized test in order to be properly
171 imaged in the tomograph.

172 The nail pull assembly (Figure 3 (b)) is positioned in a tension/compression
173 machine inside the tomograph (Figure 4). The test is performed using the test-
174 ing device developed at MATEIS laboratory (INSA de Lyon) [23] and designed

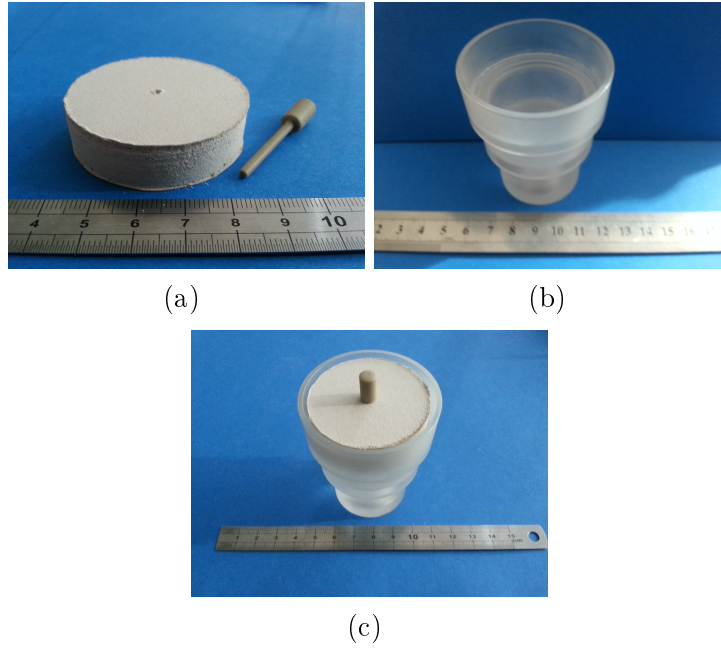


Fig. 3. In-situ nail pull setup consisting of a plasterboard circular disk through which a hole has been drilled along the central axis and a PEEK nail (a), a PMMA support (b). Once the disk has been mounted in the PMMA support, the nail head can be pushed through the specimen by an external actuator (c)

175 to be mounted on the rotary stage of the tomograph. To avoid obstruction of
 176 the X-ray beam by the testing machine during the 360° rotation, the com-
 177 pressive load applied onto the nail head is balanced by a tensile load on a
 178 cylindrical tube that encloses the test (without contact). This hollow cylin-
 179 der is made of PMMA so that the X-ray absorption is low as well as uniform,
 180 regardless of its angular position. The displacement of the upper platen is pro-
 181 vided by a stepping motor controlled by a computer. The latter also records
 182 the load.

183 The nail pull test consisted of pushing the head of the nail into the sample, un-
 184 til failure, with a velocity of $5 \mu\text{m/s}$. The load-displacement curve was recorded
 185 during the test (Figure 5). In the first part of the test, the sample was imaged
 186 at the initial state (i.e. without load) and then at 25 N of loading. Increments
 187 of approximately 50 N were applied until the load reached the plateau value

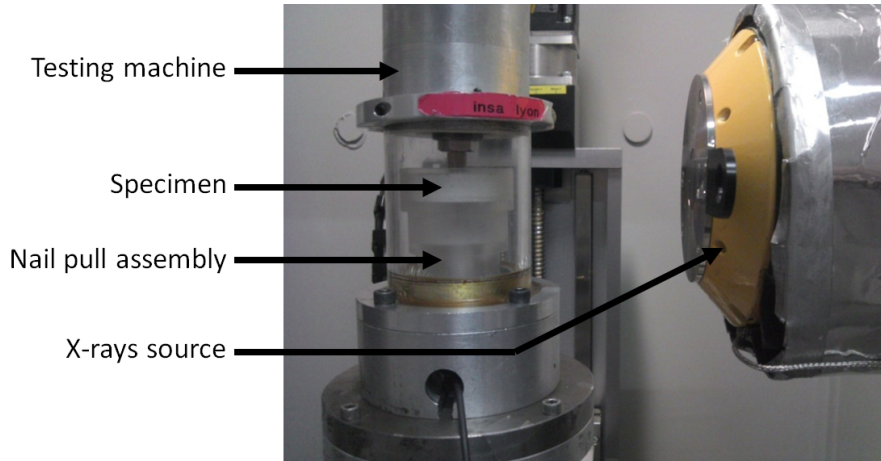


Fig. 4. In-situ nail pull test

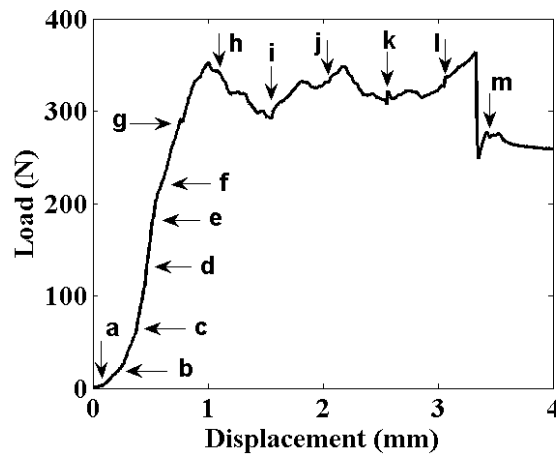


Fig. 5. Load-displacement curve of the test with 13 scans

188 (≈ 350 N in the present case, see Figure 5). Then 0.5 mm displacement in-
 189 crements were applied. After each step, the crosshead was stopped and scans
 190 were acquired after a dwell time (about 20 minutes) to prevent blur caused by
 191 the relaxation of the sample and the setup during the scan time. The sample
 192 was imaged in its initial state (i.e. without load) and at different steps of the
 193 experiment. In total, thirteen scans were acquired.

194 **3 Analysis of the failure mechanism**

195 *3.1 In-situ observations*

196 Figure 6 shows the microstructural evolution in the same vertical section close
197 to the middle axis of the reconstructed volumes for the different states (from
198 *a* to *m*) referenced in Figure 5. The section, which is parallel to the loading
199 axis, has been selected to be located slightly away from the nail axis. All scans,
200 including *a*, show a small cone crack close to the rear surface presumably due
201 to imperfect hole drilling. It will be shown later that this modest imperfection
202 has no observable influence on the test.

203 The beginning of the loading curve shows a nonlinear increase corresponding to
204 taking up play between the different moving parts. No microstructural changes
205 are observed in the corresponding scans (see Figure 6, scans *a*, *b*, *c* and *d*). In
206 particular, no cracks are visually detected in the tomographic pictures.

207 The second part of the load-displacement curve corresponds to a significant
208 slope change. By analyzing scans *e*, *f* and *g* (Figure 6), and more importantly,
209 by zooming around the nail head (Figure 7), plaster compaction is observed
210 in the upper part of the core. Compaction is caused by pore collapse. Because
211 plaster is compacted, the paper is loaded in tension and breaks. This phe-
212 nomenon cannot be observed at the chosen resolution, but is deduced from
213 the load drop in Figure 5 (between acquisitions *f* and *g*). The roller coating
214 breaks later on close to the nail edges between steps *h* and *i* (see Figure 6).
215 The compaction is thus the key point in the failure mechanism of the plate,
216 because it initiates the tearing of the front face paper lining.

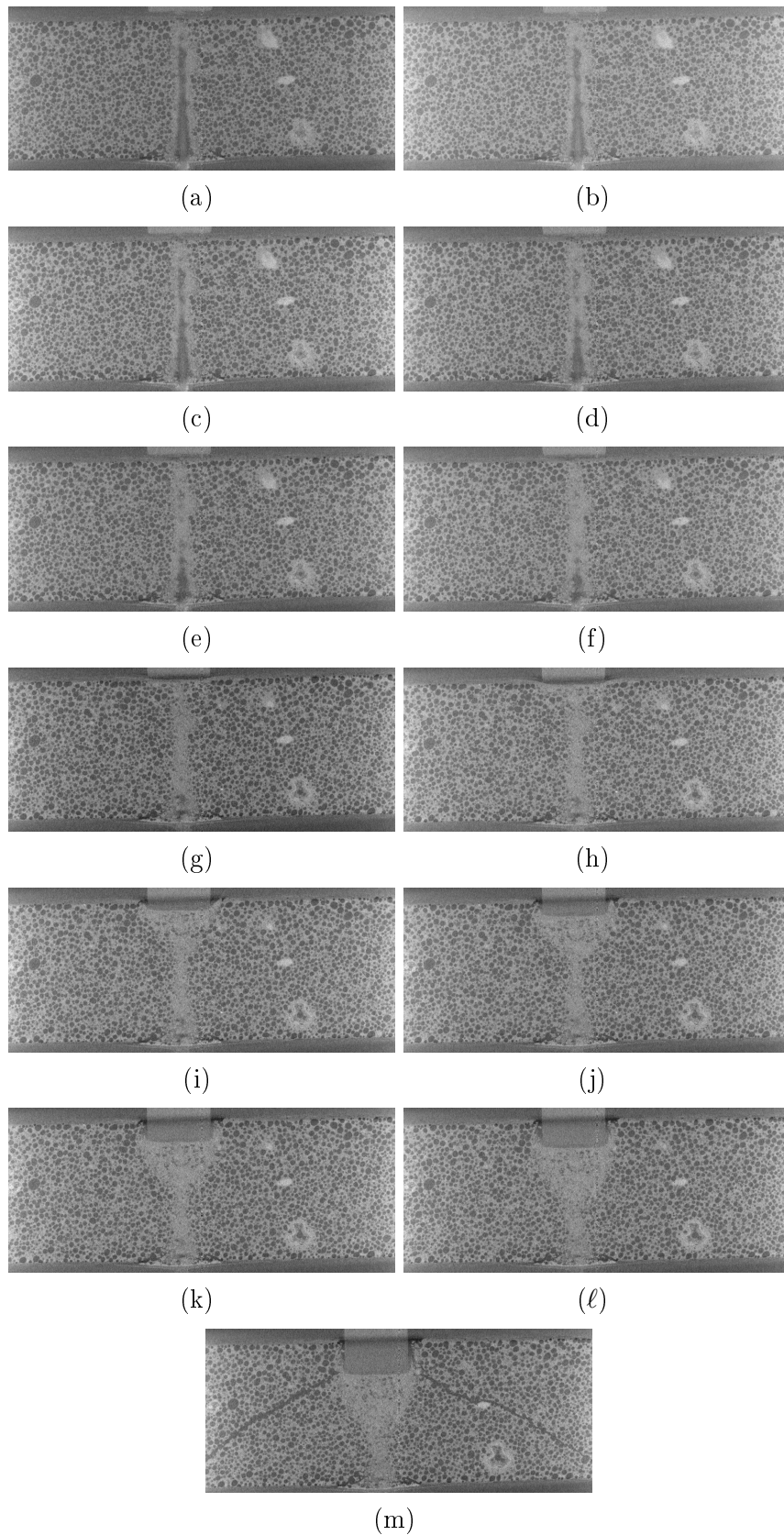


Fig. 6. Sagittal tomographic sections showing the evolution of the microstructure at different loading levels in the nail pull test. Slice (a) shows the initial state (unloaded state)

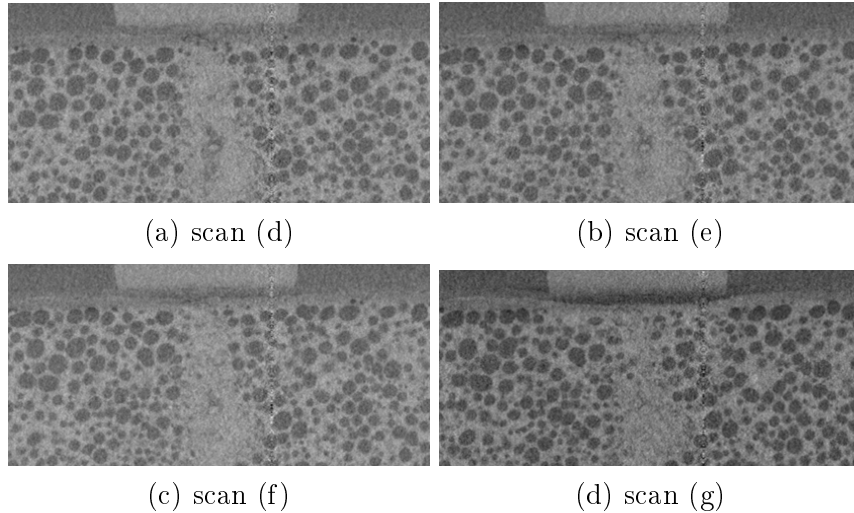


Fig. 7. Sagittal tomographic sections showing the evolution of the microstructure under the nail head for scans d to g

217 As the compaction strength is reached, the upper paper lining (together with
 218 the roller-coating) is punched by the nail head, without giving rise to a signif-
 219 icant load decrease as the paper is torn down. The applied load is then fully
 220 supported by both the core plate and the rear lining. The nail head penetrates
 221 through the core of the board sample in a compaction regime that develops
 222 over a larger region (see Figure 6, scans h , i , j , k and l). In this regime, the
 223 load stabilizes around a level of 350 N with fluctuations. This constant force
 224 can be rationalized by noting that the diameter of the compacted region is
 225 close to that of the nail head and does not vary in the plateau regime h - l .
 226 Simultaneously, the collapsed region gets longer along the nail axis. In other
 227 words, the collapsed plaster region propagates along the nail shank toward the
 228 bottom face. Thus, the penetration force is expected to remain equal to the
 229 crushing strength multiplied by the projected-compaction area in the plane
 230 perpendicular to the loading direction. This area is a ring of outer diame-
 231 ter larger than that of the nail head and inner diameter equal to that of the
 232 initially drilled hole). The mean compressive strength can be evaluated from
 233 the analyses of scan l , for which the outer diameter of the crushed zone is

234 ≈ 8.4 mm (Figure 6(l)). Since the applied load is equal to 320 N, the crushing
235 strength is equal to 6.3 MPa. This value is comparable to crushing strength
236 that was obtained in a spherical indentation test conducted on the same plas-
237 terboard [13].

238 When the nail head has penetrated about one fourth of the sample thickness
239 and the collapsed zone has reached about one half of the sample thickness,
240 the remaining thickness of the plate can no longer withstand the applied load.
241 The final failure is caused by cone-shaped cracking of the core (i.e. opening
242 mode) coaxial with the nail axis (Figure 6, scan m) giving way to the nail
243 through the specimen.

244 To analyze these observations more deeply, displacement fields and correlation
245 residuals are computed by resorting to digital volume correlation.

246 3.2 DVC analyses

247 In the present case, continuous displacement fields are measured when dis-
248 cretized over a finite element mesh made of 8-noded (C8) cubes (i.e. C8-
249 DVC [31]). Since very small strains occur, a regularized approach is pre-
250 ferred [35,36]. The regularization length will be larger than the element size
251 so that the high frequency displacement fluctuations that are not mechani-
252 cally admissible are filtered out. In the present case, a regularization length of
253 $\ell_{reg} = 30$ voxels was used.

254 The underlying hypothesis in DVC, namely the conservation of the gray lev-
255 els of the analyzed microstructure, is exploited by minimizing the correlation
256 residuals (i.e. the sum of squared gray level differences between the reference

257 volume and the deformed volume corrected by the measured displacement
258 field). In the present case, the displacement field is assumed to be continuous
259 thanks to the finite element shape functions of the C8 discretization. Conse-
260 quently, any discontinuity will be detected in the correlation residuals since
261 the chosen kinematics is not consistent with such a phenomenon [34,37].

262 To evaluate the measurement resolution, instead of acquiring only one scan
263 in the reference configuration, two scans are acquired without any sample
264 displacement [38]. The DVC code is run on these two scans and any devia-
265 tion from zero is interpreted as representative of the measurement uncertainty
266 associated with the present setup, data acquisition and processing. The stan-
267 dard displacement resolution is of the order of 0.01 voxel for C8 elements of
268 size equal to 10 voxel and a regularization length of 30 voxels. Correspond-
269 ingly, the strain measurement uncertainty, as illustrated in Figure 8(a) for
270 the reference volume, is computed to be of order 10^{-3} . Because of the fact
271 that plaster is brittle, and breaks down for low strains, the elastic deforma-
272 tion will not be resolved in the following. Figure 8(b-d) shows that the strain
273 field outside of the compacted zone cannot be measured as being significantly
274 different from 0. Nevertheless, DVC is useful to show, for instance, that cracks
275 with small opening displacement, which would not be visible directly on the
276 tomographic reconstruction, are not present. This uncertainty level is typical
277 of displacement resolutions associated with reconstructed volumes from com-
278 puted tomography [38]. The root mean square level of the correlation residuals
279 is equal to 9.6 gray levels or 3 % of the overall gray level range.

280 The displacement field of the n -th scan is assessed by correlating the n -th
281 reconstructed volume with the initial one (unloaded state, scan a , considered
282 as the reference). The Region Of Interest (ROI) over which the displacement

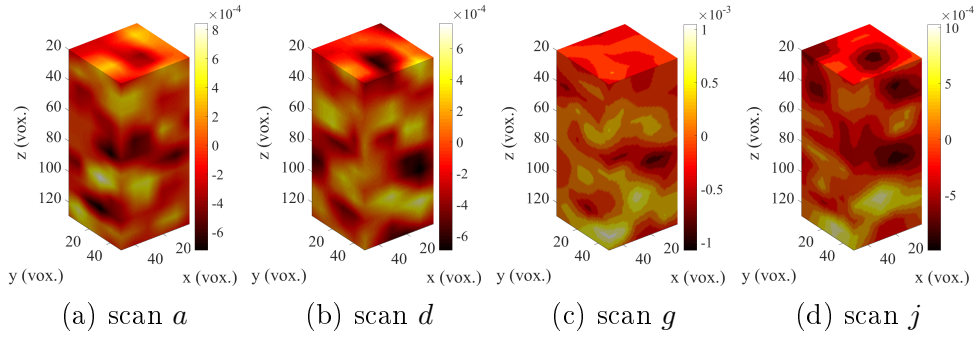


Fig. 8. (a) 3D renderings of the ϵ_{zz} strain component in the reference configuration measured by RC8-DVC, in order to assess the strain measurement uncertainty. For comparison, a similar plot for the same analyzed ROI located outside of the compacted zone is shown for different stages of loading ((b)-(d)) showing that the strain variation cannot be distinguished from noise. The subvolume analyzed here is located outside the compacted region (in the first quadrant of the global volume)

283 field is evaluated has a size of $220 \times 220 \times 160$ voxels or $5.5 \times 5.5 \times 4 \text{ mm}^3$. The
 284 size of the C8 cube element is equal to 10 voxels (or $250 \text{ }\mu\text{m}$), the regularization
 285 length is equal to 30 voxels (or $750 \text{ }\mu\text{m}$). This choice leads to a little more than
 286 23,000 unknown kinematic degrees of freedom to be measured per analyzed
 287 case. Figure 9 shows a 3D renderings of correlation residuals and displacement
 288 fields evaluated with RC8-DVC for four steps of the experiment.

289 Figure 9(a), i.e. state *d*, shows the displacement fields measured just before
 290 the change in slope of the loading curve (Figure 5). The displacement am-
 291 plitudes are very small (i.e. less than 1 voxel or $25 \text{ }\mu\text{m}$) and are mostly due
 292 to a rigid rotation of the sample. Most of the displacement fluctuations are
 293 caused by measurement uncertainties, as will be shown below later. Further,
 294 the correlation residuals have very small levels (RMS level equal to 9.8 gray
 295 levels, which is very close to that observed when no motion was applied to
 296 the sample, namely, 9.6 gray levels). In addition, no cracks are detected. From
 297 these observations, and those as shown below, it is concluded that up to step
 298 *d* of the nail pull test, the DVC resolution does not allow the motion of the
 299 plasterboard core to be distinguished from that of a rigid body.

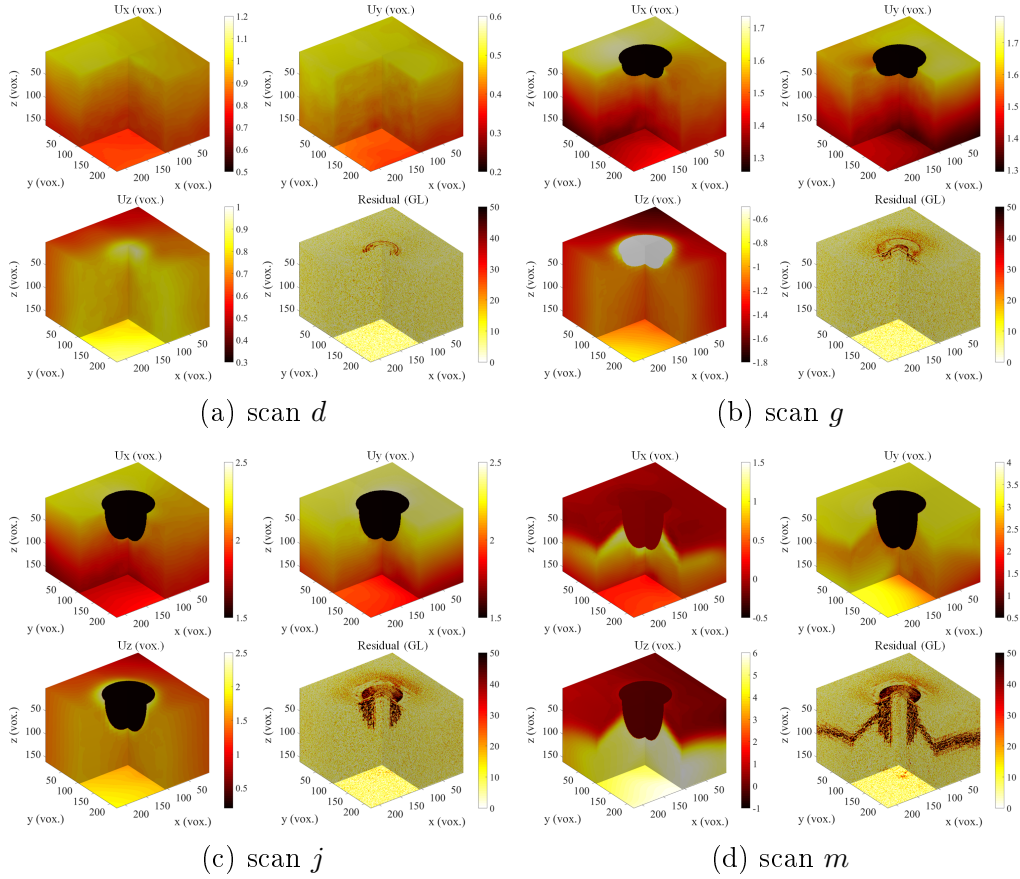


Fig. 9. 3D renderings of correlation residuals and displacement fields evaluated with RC8-DVC for four steps of the experiment. The loading direction is z and the displacements are expressed in voxels ($1 \text{ voxel} \leftrightarrow 25 \mu\text{m}$). The correlation residuals are expressed in gray levels (the dynamic range of the reconstructed volumes is 256 gray levels). The compacted zone is masked in the displacements fields

300 Figure 9(b) (state g) corresponds to the load level just before the tearing of
 301 the upper paper lining and roller coating (Figure 6 scan g). Away from the nail
 302 head, the measured displacement ranges still have very low levels (i.e. less than
 303 one voxel or $25 \mu\text{m}$). In the vicinity of the nail head, the correlation residuals
 304 increase significantly. In the present case, this result indicates a deviation
 305 from the conservation of gray levels due to pore collapse. In this region the
 306 initial microstructure is completely lost. Even though a displacement field is
 307 reported for this region, it is not trustworthy. In fact, this region is masked for
 308 DVC and a basic interpolation is provided to define the displacement over the
 309 whole region. This procedure allows for the computation of residuals and thus

310 gives access to the boundary of the crushed region very accurately. A similar
311 procedure was used to analyze the kinematics of an indentation test on the
312 same material [39].

313 Figure 9 (c) shows the displacement fields measured in the middle of the com-
314 paction plateau (Figure 6, scan j). The size of compacted region has signifi-
315 cantly increased (as can be judged from the correlation residuals). Its boundary
316 was still sharp with respect to the remainder of the sample, which underwent
317 very small displacement levels. At this late stage of loading, no crack is de-
318 tected on the correlation residuals (even when this field is carefully inspected
319 in 3D). It is therefore concluded that, at the resolution of the images, no crack-
320 ing occurred and that the main degradation mechanism was the compaction
321 of the plaster core under the nail head.

322 The displacement field measured from the last scan, m , has a totally different
323 character as compared to the previous cases (Figure 9(d)). A steep displace-
324 ment gradient indicative of a discontinuity is clearly observed, which shows the
325 presence of the cone crack leading to the final failure of the sample. The trace
326 of the crack is also present in the correlation residuals. In addition, the com-
327 pacted zone displays only a slight progression when compared to the previous
328 state l (not shown here). The occurrence of the cone crack can be connected
329 to the very abrupt drop in the penetration force applied onto the nail, as the
330 cone opening gives way to the nail perforation. This observation is consistent
331 with 3D renderings of the corresponding scan in the reference configuration
332 (for which no crack is visible) and the deformed configuration (Figure 10)

333 Associated with the C8 discretization, the mean Green Lagrange strains are
334 computed over each element [32]. The major positive eigen strain, hereafter
335 termed “equivalent” strain, ϵ_{eq} , is a scalar invariant component that is very

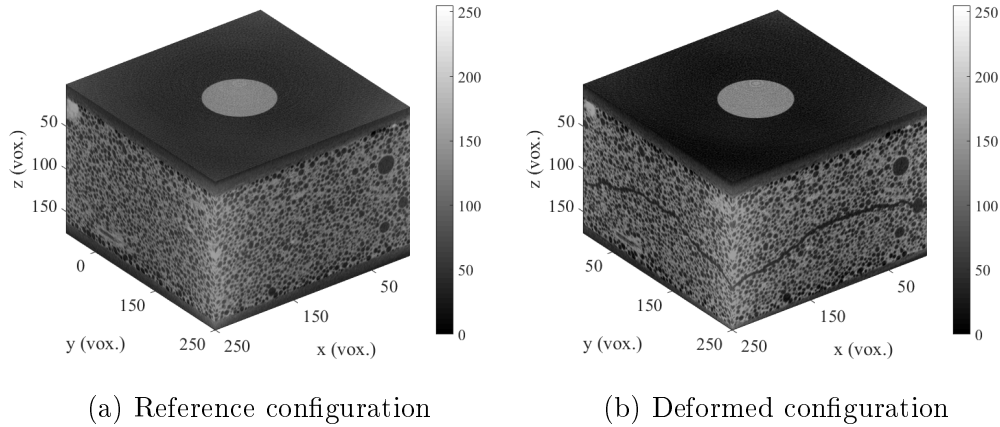


Fig. 10. (a) 3D rendering of the microstructure of foamed gypsum to be subjected to nail pull test. (b) The crack is visible on the lateral faces of the sample (the dynamic range of the reconstructed volumes is 256 gray levels)

336 suited to reveal crack formation irrespective of their orientation. 3D rendering
 337 of the equivalent strain is shown in Figure 11. As previously discussed, the
 338 crushed region is masked. Outside of it, the amplitude of the equivalent strain
 339 (see Figure 11(a), (b) and (c)) measured by RC8-DVC is very low. Because
 340 it is the largest (positive) eigenstrain, random fluctuations of zero mean will
 341 give rise to a positive mean value for ϵ_{eq} that should not be confused with the
 342 statement that strains (apart from the presence of the final cone crack) are in-
 343 distinguishable from 0. At the last scan, the crack that leads to the breakdown
 344 of the sample can be clearly seen from the apparent strain field (Figure 11(d)).
 345 It is “apparent” because the displacement discontinuity is distributed over the
 346 element size. The crack opening is more easily read from Figure 9(d), although
 347 it is not uniform (ranging from 2 to 4 voxels, or 50 to 200 μm), because of a
 348 relative rigid body rotation of the two parts.

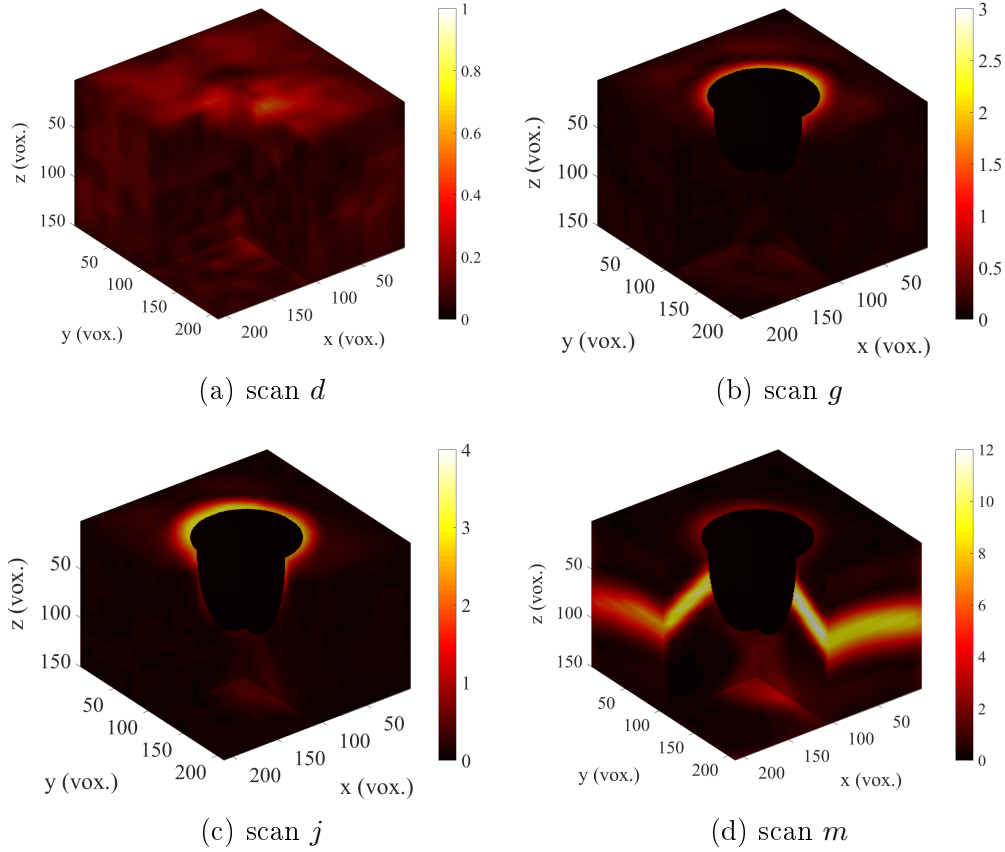


Fig. 11. 3D renderings of major principal strain ϵ_{eq} in % obtained from DVC results. Because of the value of the correlation residual is high in the compacted area under the head of the nail, this area is hidden in the major principal strain fields

349 4 Discussion

350 Some studies have dealt with the analysis of failure mechanisms in nail pull
 351 tests. Peterson [5] carried out many tests (boards with/without top/bottom
 352 papers), following the ASTM C473 protocol. The author proposed the follow-
 353 ing steps based upon the post-mortem analyses. First, the initiation of radial
 354 cracks at the rear face of plasterboard was observed for a load level of 130 N.
 355 The presence of the rear-side paper prevented complete failure from occurring.
 356 Then, at a load varying between 130 N and 230 N, a circumferential crack with
 357 a diameter of about 25 mm was visible on the rear face of the plate. With the
 358 increase of the load level the crack propagated toward the edge of the nail

359 head. A further increase of the load led to shear failure, which occurred imme-
360 diately below the nail head when the maximum load was reached (≈ 360 N).
361 In the present case, this chain of events is not observed. For the investigated
362 plasterboard, core cracking occurs at the last loading step. Significant pore
363 collapse is observed prior to the final failure.

364 Kuntze [3] reported different observations about nail pull tests performed on
365 comparable lightweight plasterboards. The author observed that a cone crack
366 was formed under the nail head, but propagated downward. A similar obser-
367 vation was also reported for gypsum boards by British Plasterboard Research
368 laboratories [6]. In the present analyses it is not possible to conclude whether
369 the final crack has initiated close to the nail head or from the opposite side.

370 Byford *et al.* [7] also studied the nail pull strength. A series of tests was
371 performed on two types of industrial plasterboard. To investigate the failure
372 mechanism two methods were used, first an SEM analysis was carried out
373 on the polished samples. The second method was X-ray radiography. The
374 latter technique was used for detecting flaws such as cracks and voids. Up to
375 0.5 mm nail penetration, no irreversible damage or displacement was observed,
376 consistently with a purely elastic behavior. Then, a phase of compaction of the
377 upper part of the core associated with damage and tearing of the upper paper
378 facing was reported. The compaction of the upper part of the gypsum core was
379 considered as the critical factor in the failure mechanism. These observations
380 are identical to the present analyses, in particular the fact that the compaction
381 mechanism is controlling the resistance of plasterboard subjected to nail pull
382 test.

383 Tests also performed on samples where the lower paper surface was removed
384 showed that shear cracking occurs for similar displacement levels. However,

385 the lower paper facing contributed significantly to the stiffness of the board
386 and hence the result cannot be simply transposed to full plasterboards. Al-
387 though this study aimed at identifying the failure mechanisms of plasterboard
388 in the nail pull test, the observation of interrupted tests (i.e. for different ap-
389 plied load levels) is difficult and cumbersome (i.e. many samples need to be
390 analyzed), and the onset of the different stages is unprecise. The method used
391 to test the plasterboards was not really applicable to identifying the critical
392 stage of failure as the interruption at very few stages gives a coarse view, and
393 the considered penetrations were too aggressive as compared to the typical en-
394 countered failure loads. In the present case, tomography coupled with in-situ
395 nail pull test allows the various mechanisms to be analyzed non destructively
396 on a single sample.

397 Cantwell [8] conducted a comparable study to that of Reference [7] aiming
398 for the identification of the different stages of failure in nail pull tests on
399 three types of industrial plasterboard. Interrupted tests were selected as the
400 strategy to have access to the different stages of degradation. Microcracking
401 and/or local collapse of the porosity was the first observed step in the failure
402 process. At 40% of the ultimate load, the author observed pore collapse and
403 the formation of a compacted zone in the area of the nail head. Crushing of the
404 plaster foam resulted from inter-crystalline slip, intra-crystalline shear and/or
405 fracture of gypsum crystals. The author interpreted the following stage as the
406 collapse of the porous plaster, together with the coalescence of microcracks. At
407 80% of the ultimate load the top paper was finally perforated along the edge
408 of the nail head. A densified region developed under the nail head, which was
409 completely separated from the upper paper. At the end of the test permanent
410 strains were observed in the paper and the core of the plate. Lateral cracks
411 appeared in the top roller coating layer and at the interface between the roller

412 coating and the core of the plate. High densification due to the collapse of the
413 porosity under the nail head was also reported. In the present case, the same
414 degradation scenario is observed. However, given the chosen resolution (i.e.
415 25 μm) it is not possible to discuss the microscopic origin of the mesoscopic
416 observations. High resolution tomography may allow for such investigations.

417 5 Conclusions and perspectives

418 In this work a comprehensive analysis of the standardized nail pull test has
419 been proposed. Thanks to X-ray tomography, *in-situ* mechanical testing and
420 digital volume correlation, the degradation mechanisms of lightweight plaster-
421 board in the nail pull test have been identified. After contact between the nail
422 head and the sample surface, no evidence of damage is observed up to about
423 half of the peak load. As soon as compaction of the core starts, as observed
424 through the inception of a densified layer under the nail head, the top paper
425 lining is torn and the roller coating fails. This compaction is thus very clearly
426 the critical factor that controls the plateau stress, with no sign of load over-
427 shoot when the paper facing and roller coating give way to the nail. After this
428 stage, the penetration of the nail takes place under constant load, which cor-
429 responds to the compaction phase of the plaster core in a cylindrical region of
430 fixed diameter close to that of the nail head, and increasing length as the nail
431 penetrates further in the core. When the penetration reaches a depth of about
432 25 % of the initial thickness of the plasterboard, the final failure of the sample,
433 by cone cracking of the core, occurs abruptly. The post-crack resistance only
434 comes from the paper backing, which has to be torn down to free the nail.

435 The above conclusions are drawn from the analysis of reconstructed volumes

436 acquired at different steps of the nail pull test. The analysis of tomographic
437 observations by digital volume correlation was also conducted and shows, in
438 particular, that local crushing of the upper part of the core of the plate is lo-
439 cated directly under the nail head prior to the failure of the front paper lining.
440 Measured displacement fields confirm the degradation mechanisms observed
441 from the tomographic scans. They also indicate that no crack initiates until
442 the very end of the experiment at the chosen resolution (i.e. 25 μm per voxel)
443 Consequently, the compaction role of the plaster foam core entirely determines
444 the nail pull resistance for the system under study.

445 The fact that compaction is observed in the nail pull test reported herein
446 and in an indentation test on the same material [39] proves that the latter is
447 representative of the former, even though the indenter shape is very different.
448 This can be explained by the fact that as soon as the compaction zone develops,
449 the role of the indenter itself is minimal since the boundary of compacted zone
450 is itself the effective indenter further loading the intact foamed plaster. The
451 fact that a compaction zone grows is beneficial to the plasterboard as it does
452 not localize in very small regions where the material may no longer be able to
453 sustain the applied load. The observed plateau of the penetration force for a
454 displacement covering a significant fraction of the board thickness prevents a
455 brittle failure that would be detrimental to safety.

456 Whilst the observations and conclusions made herein are specific to the stud-
457 ied plasterboard, the present methodology, where a wealth of information is
458 accessible, may be followed to analyze other brittle foams. For such problems
459 where different mechanisms are intricate, the geometry is confined and hidden
460 to surface observations, mechanical tests conducted in-situ in a tomograph are
461 invaluable.

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