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STRUCTURAL TESTING OF LOCAL BUCKLING FOR THE DESIGN OF SANDWICH AIRCRAFT STRUCTURES

Ginot Malo^{a,b}, Castanié Bruno^a, Bouvet Christophe^a, Mahuet Nicolas^a

a: Institut Clément Ader, Université de Toulouse, INSA – ISAE-SUPAERO – UPS – IMT Mines Albi, 3 rue Caroline Aigle, Toulouse 31400, France

b: Elixir Aircraft, Rue du Jura, 17000 La Rochelle, France

Abstract: *The design of light aircraft sandwich structures is often driven by a local buckling phenomenon named “wrinkling” which can be the primary cause of failure of such structures. Structural tests using the VERTEX Methodology were performed to access the wrinkling behaviour of technological sandwich specimens representative of the technology of Elixir Aircraft. The operating principle of the VERTEX machine is the use of four hydraulic actuators to load a rectangular box structure and therefore, sandwich panels were tested under compressive and shear loading. Wrinkling is observed thanks to Digital Image Correlation (DIC) and a high-speed camera. At this level of the test pyramid for certification of aeronautic structures, the observation of wrinkling on sandwich panels remains rare in literature and may lead to interesting future investigations on the experimental VS numerical finite elements model's dialogue.*

Keywords: Local buckling; Wrinkling; Sandwich structures; Structural testing; Light aircraft

1. Introduction

Thanks to their high specific bending stiffness, sandwich structures have been widely used in aviation for more than a hundred years (1). Recently, they are increasingly used for primary structures for lightweight aviation (like the Elixir from Elixir Aircraft®, certified by the EASA in June 2020). Local buckling phenomenon named “wrinkling” can be the primary cause of failure of such structure (1). An effective methodology for wrinkling sizing is still under discussion (2), and experimental studies could discriminate between existing models. However, experimental tests on the wrinkling phenomenon in the literature are still scarce. Previous works have shown, at beam scale (most experimental studies in literature), the high sensitivity of the phenomenon to boundary conditions and initial geometrical defects leads to difficulties in correlating experiments and models (3)(4)(5). An interesting approach consist in studying the upper-stage of the “pyramid of tests” called “technological”, in other words, switching from beam scale to panels. This, to characterize the true behaviour of a structure and reduce the influence of boundary conditions. Therefore, this paper aims to offer protocols/methods with results and analysis of sandwich panels, tested under compressive and shear loading, where wrinkling type failure is observed. For this purpose, the VERTEX test bench (Figure 1) developed by Castanié *et al.* and first used by Serra *et al.* (6)(7)(8) was used. The operating principle of the VERTEX machine consists of four hydraulic actuators used to load a rectangular box structure. The tested panel closes the upper part of the central box. Actuators 1&2 can push or pull symmetrically to bend the box structure of the bench, thus the tested panel is locally loaded in tension or compression. Similarly, actuators 3&4 can push to twist the centre of the box structure, thus the tested panel is locally loaded in shear.

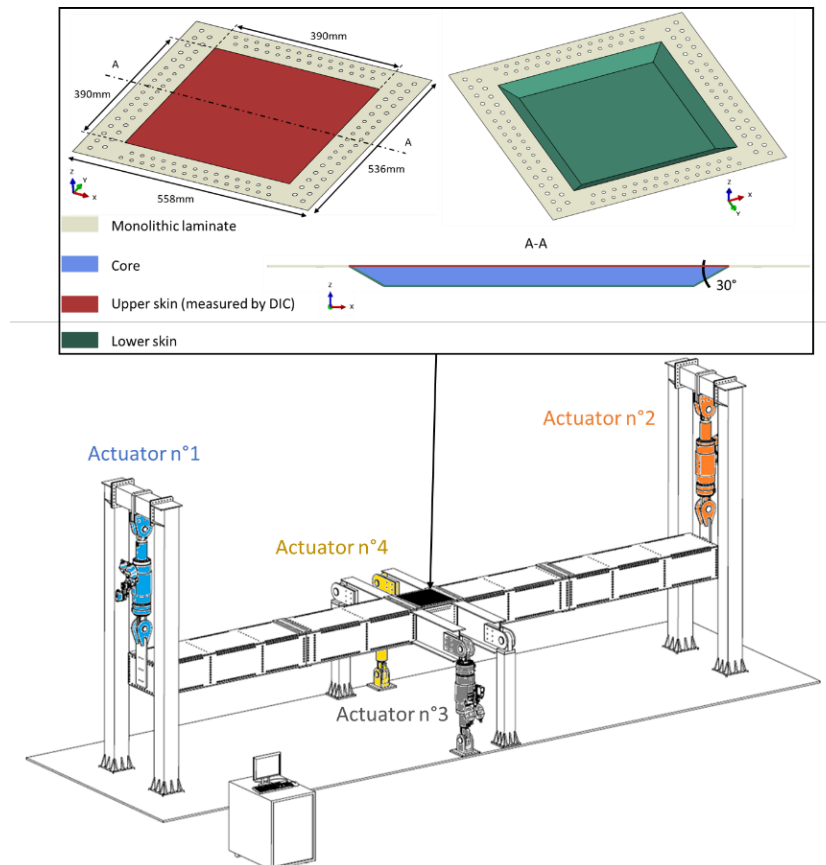


Figure 1: Vertex test rig and sandwich plate specimen

2. Materials and methods

The specimens are sandwich plates with a tapered area to close the sandwich at the centre. As a result, edges are monolithic and can be drilled to bolt the specimen to the VERTEX test bench. The specimen is positioned as shown in Figure 1 and bolted on its 4 sides with 128 screws. The external dimensions are 558x536mm², and the sandwich area with the tapered regions is 390x390mm² and 21 mm thick.

2.1 Specimen design

2.1.1 Geometry: The lower skin of the sandwich plate is not accessible as it faces the test bench box structure (Figure 1). The observable surface is the upper skin, it is thus imperative to localise the wrinkling mode on it. In the case of compressive loading, the tapered asymmetric geometry of the plate allows the upper skin to be more loaded than the lower skin and therefore to buckle. This mismatch between the load introduction axis and the mean geometric plane of the sandwich structure leads to a local bending moment, which induces an additional compressive load in the upper skin and a tensile load in the lower skin (blue arrows in **Erreur ! Source du renvoi introuvable.**). This phenomenon was already explored in asymmetric sandwich structures by Castanié *et al* (9).

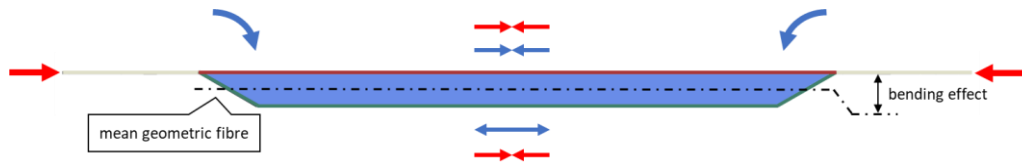


Figure 2: Bending effect on asymmetric sandwich structures.

2.1.2 Materials and process: The materials used for the specimens are ROHACELL HERO[®] 51 kg/m³ foam for the core and prepreg epoxy/carbon woven fabric for the skin. An autoclave following a "one-shot/co-cured" process is used. The trimming and drilling are carried out using a CNC (computer numerically controlled) machine.

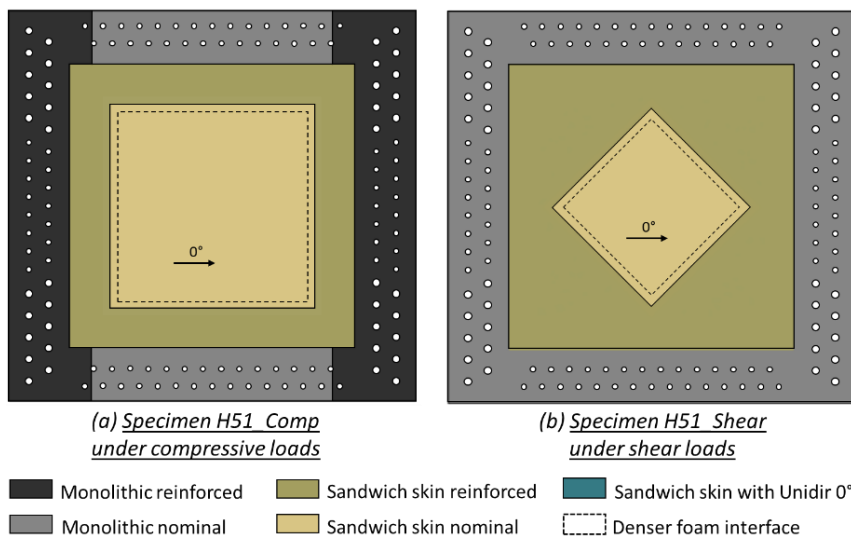


Figure 3: Skin definition

To localise the wrinkling in the centre of the plate, a high-density foam frame is used to reinforce the tapered area of the sandwich where local stresses could be relatively high. For the specimen under compressive loads (H51_Comp), the nominal area is 260x260 mm (dotted frame in Figure 3(a)). For the specimen under shear loads (H51_shear), the nominal area (dotted frame in Figure 3(b)) is lozenge-shaped of 172x172 mm to have perpendicular edges to the main stresses at 45°. For the same reasons, skins in the tapered area are reinforced (deep brown area in Figure 3). For the specimen under compressive loads, the monolithic is reinforced in the specimen height (dark area in Figure 3(a)), to avoid bolt bearing. In the width, the monolithic is left with a relatively thin laminate (grey area in Figure 3(a)) so that this area does not carry all the loads at the expense of the sandwich zone. For the specimen under shear load, the nominal skin (light brown area in Figure 3(b)) is lozenge-shaped. It should be noted that skin reinforcement and core reinforcement are not in the same areas. We call nominal area (where wrinkling is expected) the area where the upper skin stacking sequence corresponds to two +/- 45° ply woven fabrics for H51-Shear specimen and a +/-45° and 0°/90° ply for H51_Comp.

2.2 Instrumentation

Because of numerous structural redundancies in the VERTEX test bench, nowadays, there is still no direct transfer function that links actuator forces with stress flows entering the specimen. An in-situ strains measurement method had to be used to calculate the stresses entering the specimen. Digital Image Correlation (DIC) has been shown to be a very reliable method, and

already been used on previous VERTEX tests (7)(8)(10). Moreover, stereo-DIC allows to measure out-of-plane displacements and reconstruct the 3D shape evolution. This is particularly useful for the wrinkling observation which manifests as short out of plane waves in the skins. To achieve this DIC, a speckled pattern is made on the upper faces of the specimens. A high-speed camera (7000fps) is then used to observe a potential explosive failure. In lower skin, “Rosette” gauges are used.

3. Results

3.1 Deformation fields: stereo-correlation

Figure 4 shows in-plane deformation fields obtained by DIC of the specimen’s upper faces, just before failure. In the nominal area, the deformations are mainly uniform and follow typical expectations. For specimen H51_Comp, shear is observed at the corners, but is nearly zero in the central nominal area (see ϵ_{xy} ’s field of H51_Comp). For specimen H51_shear, the average principal compressive strain direction is about 38° from the x-axis. Some traction is shown by the non-null xcomponents (see positive ϵ_{xx} ’s field of H51_Shear), a consequence of an inherent machine behaviour when operated for this solicitation. Local gradients (see ϵ_{xx} ’s field of H51_Comp and ϵ_{xy} ’s field of H51_Shear) at the edge of the nominal area indicate local bending induces by wrinkling waves.

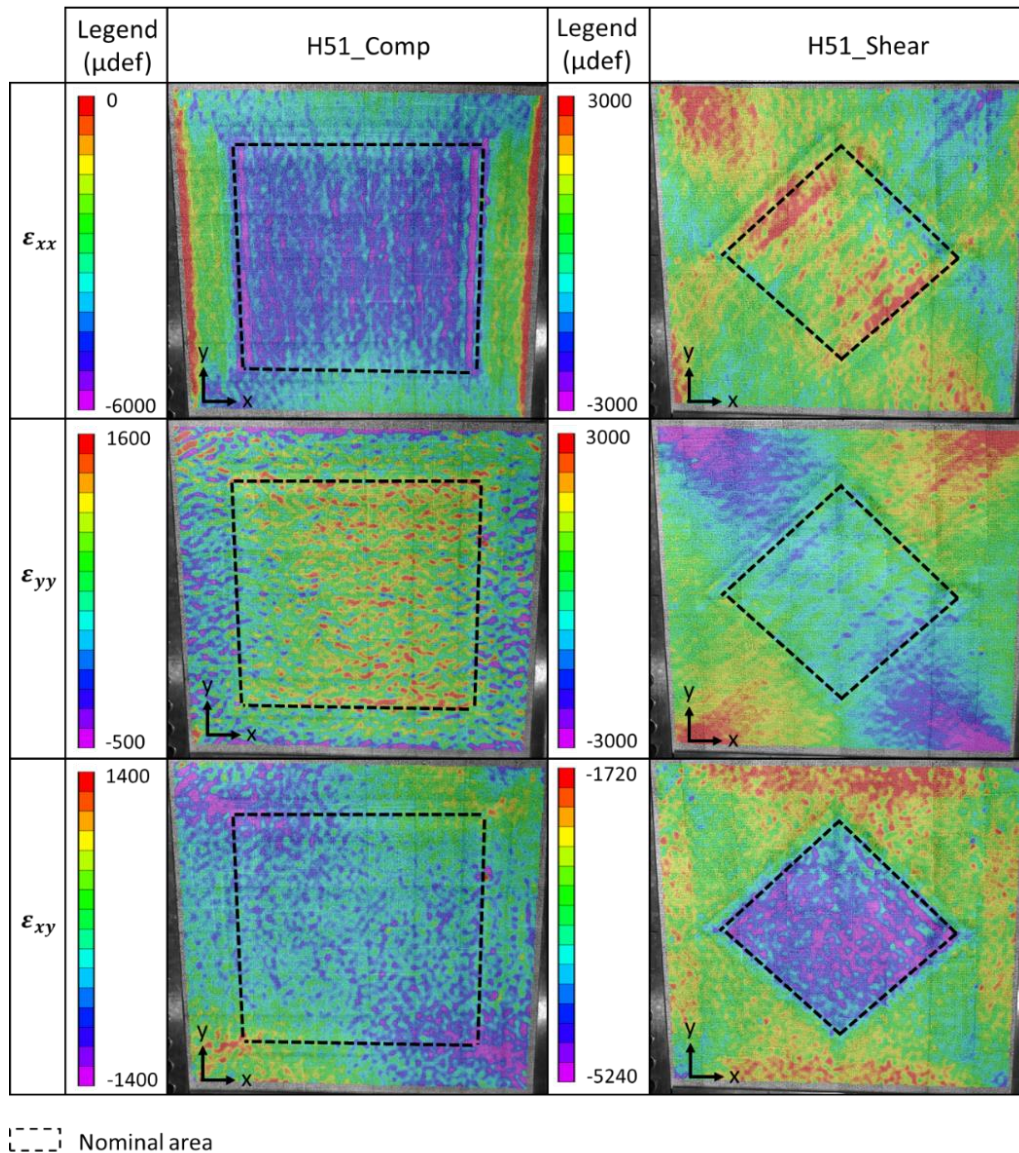


Figure 4: Deformation fields obtained by stereo-correlation.

3.2 Failure scenario

For both specimens, the failure behaviour is similar (Figure 5). The specimens fail by wrinkling the upper skin, which validates the design of the specimens. The wrinkling wave appears at the interface between the nominal HERO 51 foam and the denser foam. The core is crushed, and the wave then spreads over the width. Finally, the core fails in tension and the wave moves on a large part of the nominal area. This lasts about 2 milliseconds. For specimen H51_shear the wrinkling wave appears at -45° direction, induced by the compression along the +45° direction associated with shear loading. Skin static failure is observed from the edge of the specimen after the wrinkling event. Note that failure scenarios could be accurately reconstructed thanks to the high-speed camera.

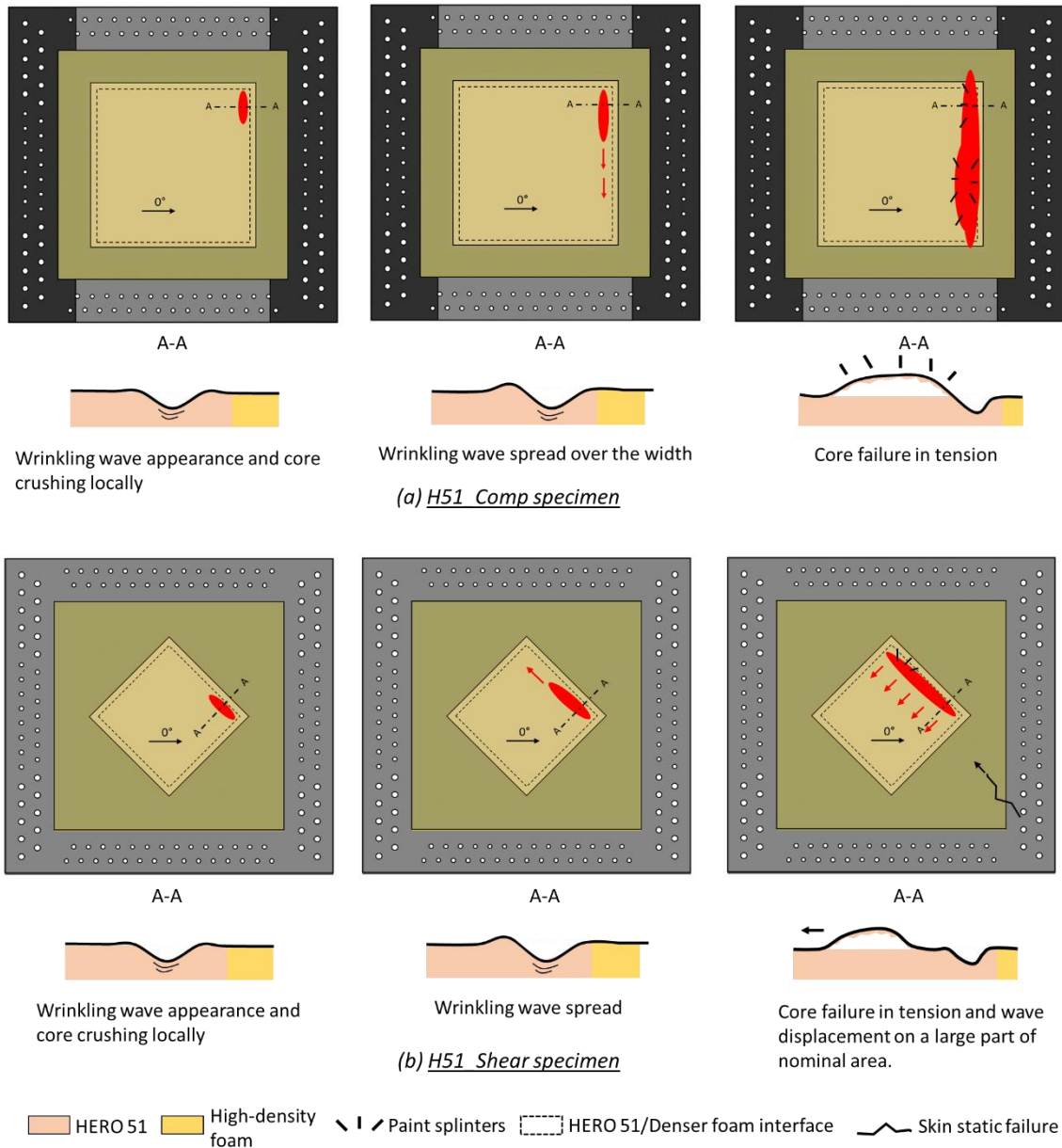


Figure 5: Failure scenario schemes

3.2 Out of plane behaviour

H51 Comp: The specimen plate bend globally (Figure 6 (a)), a consequence of the tapered asymmetric geometry. ϵ_{xx} at the center of both skins highlight the non-linear bending behaviour of the tested plate, with the upper skin showing higher loading (Figure 6 (b)).

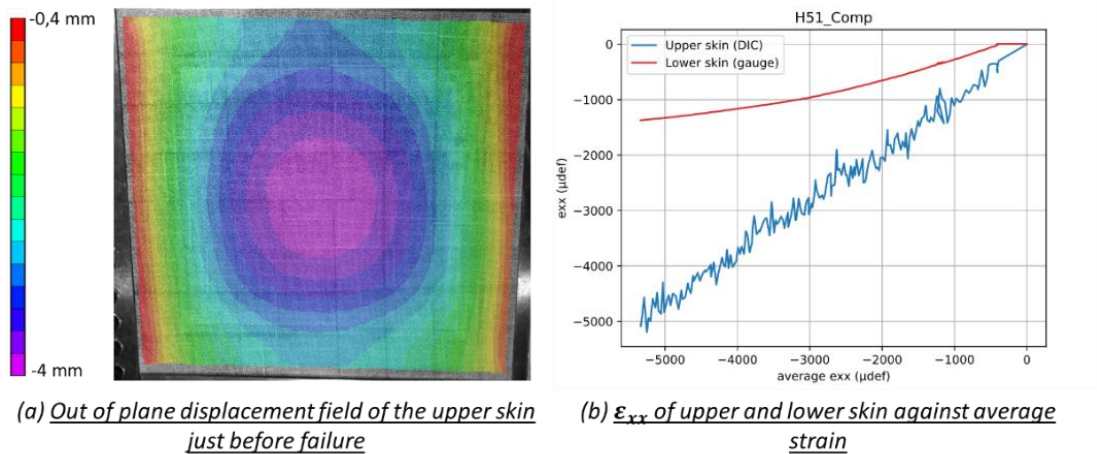


Figure 6: Specimen H51_Comp out of plane behaviour

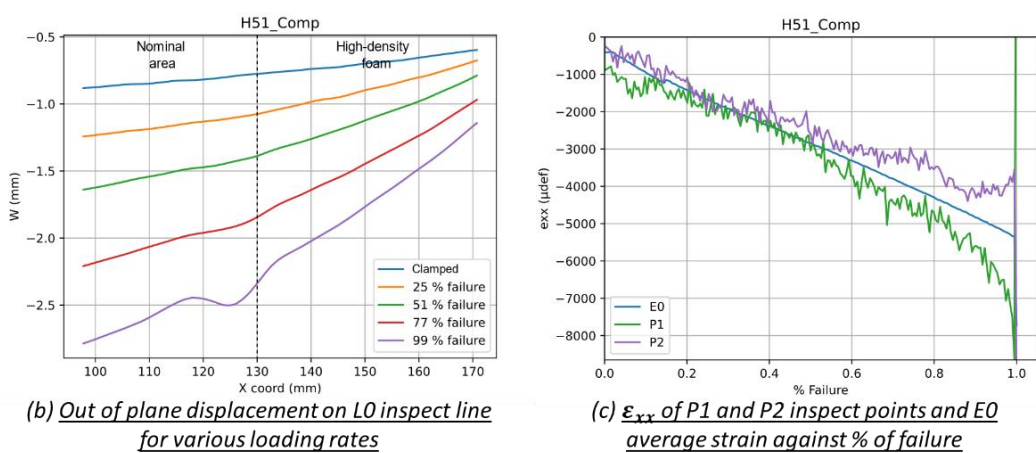
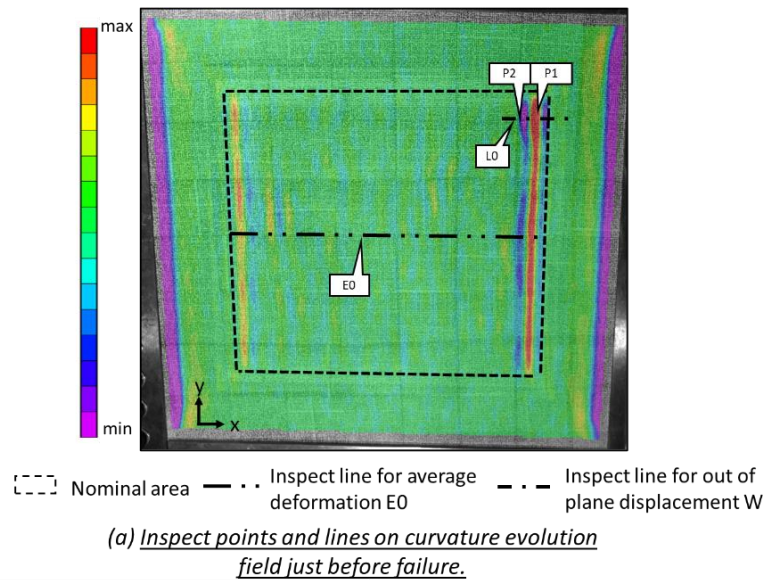


Figure 7: Specimen H51_Comp local behaviour

A wrinkling wave is observed at the interface between the nominal HERO 51 foam and the high-density foam (Figure 7(a) and (b)). It appears at the end (>80%) of the test (Figure 7(b)). This can be confirmed by looking at in-plane deformation curves (Figure 7(c)). ϵ_{xx} at P1 and P2 first

decreases linearly with load, until the apparition of the wrinkling wave (around 80% load). It then becomes non-linear, a consequence of a local bending due to the wrinkling wave. The slopes at P1 and P2 differ from the one of the average deformation E0. This is a consequence of the out-of-plane effects of the initial conditions. Since geometrical defects localise wrinkling, it has occurred near the interface with the densified foam, where an initial slight skin depression was observed thanks to DIC. This phenomenon is local, thus the non-linearity does not influence the average deformation E0 which remains linear until failure.

H51_Shear: In this specimen, the global bending behaviour presented previously is not present because the tension and compression at 45° compensate for each other. Wrinkling waves are observed in a major part of the nominal area. The maximum wave's amplitudes are observed at the interface between the nominal HERO 51 foam and the denser foam (*Figure 8(a) and (b)*), where an initial slight skin depression was observed thanks to DIC.

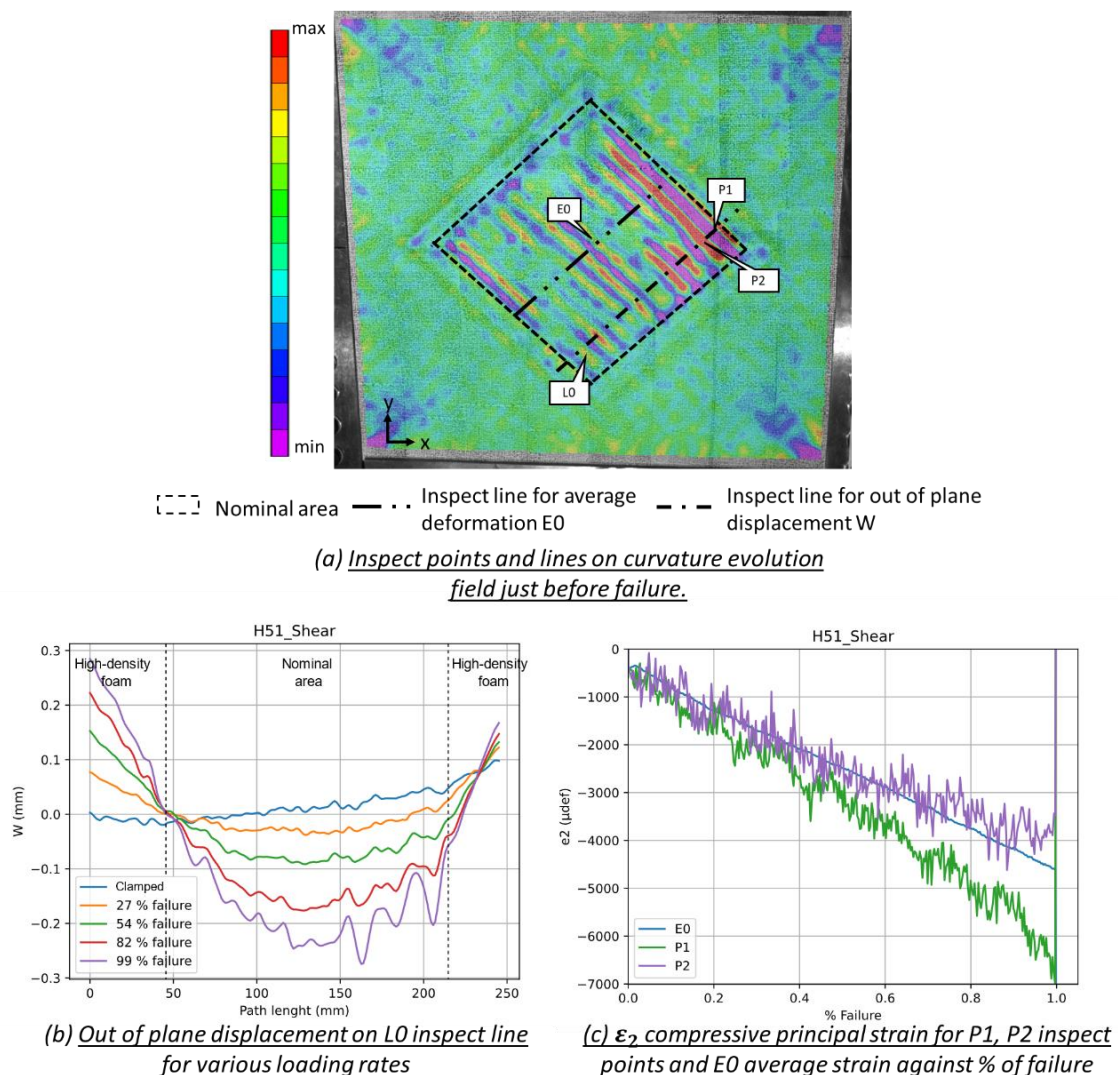


Figure 8: Specimen H51_shear local behaviour

Similar to the compressive test, ϵ_{xx} first follows a linear trend with loading, followed by a non-linear regime at the end of the test for inspect points P1 and P2. Again this can be attributed to the local buckling onset that has happened around 80% load (*Figure 8(c)*).

4. Conclusion

This paper presents the materials and methods with the associated results and analysis, of two sandwich plates bolted on 4 sides, tested respectively in compression and shear using the VERTEX test bench. Wrinkling type failure was observed using both DIC and a high-speed camera. Such specimen geometry, material definition and measurements tools have demonstrated their effectiveness to observe wrinkling and insulate the failure scenario from the influence of the boundary conditions. It's appeared that wrinkling is driven by initial geometrical defects which localise the failure. 3D shapes and local deformations rates have been quantified and should be compared with existing models. This will be the object of future works.

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