Seeing Inside Autoclave: Fiber-Optic Shape Sensor for Measuring Consolidation Deformation

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1. Introduction

In the manufacturing of composites aerostructures using thermosetting resins, prepregs are stacked in multiple orientations and cured under heat and pressure in an autoclave. During curing, the thermosetting resin undergoes a transition from a liquid to a solid state through gelation. Before gelation, however, non-uniform pressure distributions generated within the laminate cause the resin and fibers to flow. As a result, thickness variations and fiber waviness can develop around prepreg gaps/overlaps and corner regions (Fig. 1).

Because such manufacturing defects significantly affect the final mechanical properties and dimensional accuracy of composite structures, extensive research has been conducted over several decades to achieve high-precision manufacturing. However, direct observation of composite behavior inside a sealed autoclave has been difficult. Consequently, most previous studies relied on post-cure cross-sectional observations and geometric measurements, making it challenging to directly determine when and how consolidation deformation occurred and to clarify the underlying mechanisms. Therefore, a new measurement technique capable of supporting the development of high-precision manufacturing processes based on a mechanistic understanding of consolidation deformation has been strongly desired.

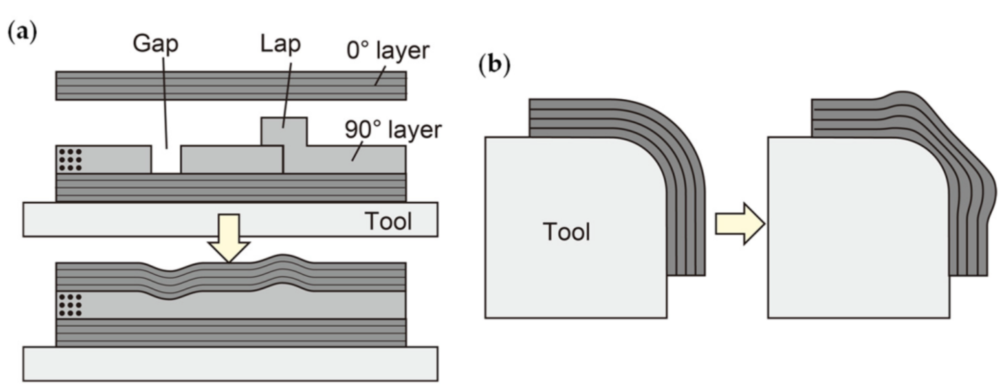

Figure 1. Consolidation deformation occurring before resin gelation: (a) prepreg gap/overlap region, (b) corner region.

To address this challenge, the authors' research group has developed a technique for monitoring consolidation deformation of composites inside an autoclave using fiber-optic sensors. A key advantage of fiber-optic sensors is their small diameter (less than 150 μm), which allows them to be embedded within composite materials without significantly affecting the material properties while enabling in-situ measurement of internal states. The following sections introduce an embeddable strip-type fiber-optic shape sensor newly developed for monitoring consolidation deformation.

2. Embeddable Strip-Type Fiber-Optic Shape Sensor [1]

The basic principle of embedded fiber-optic strain sensing is that a flexible optical fiber sensor deforms together with the surrounding material, resulting in the same strain being experienced by both the sensor and the host material. However, while the resin remains in the liquid state, the embedded optical fiber is not firmly bonded to the composite and can slip relative to the surrounding material when consolidation deformation occurs. Furthermore, conventional fiber-optic strain sensors measure the strain at the fiber core located at the center of the cross-section, i.e., on the neutral axis. Consequently, even when the embedded optical fiber is bent by consolidation deformation, little or no strain change is detected. One possible solution is to use multicore optical fibers with multiple cores located away from the neutral axis, allowing bending strains to be measured. However, because multicore fibers have a circular cross-section, they can easily undergo axial twisting within the composite laminate, leading to reduced measurement accuracy.

To overcome these limitations, the author research group developed an embeddable strip-type fiber-optic shape sensor for composite materials (Fig. 2). The sensor consists of optical fibers integrated on the upper and lower surfaces of a thin plastic strip, with the fiber cores located away from the sensor neutral axis. Therefore, bending deformation of the sensor induces bending strains in the optical fiber cores. In addition, the strip geometry prevents axial twisting because the sensor is constrained between adjacent plies when embedded in the laminate.

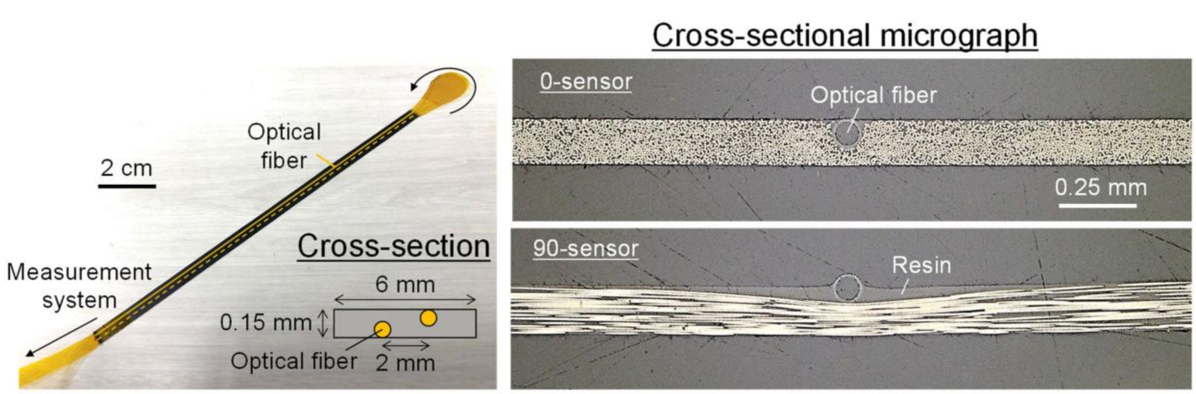

Figure 2. Embeddable strip-type shape sensor [1] (left: a single optical fiber integrated on the upper and lower surfaces of a plastic strip; right: two sensors with different stiffnesses fabricated from cured prepregs with different fiber orientations).

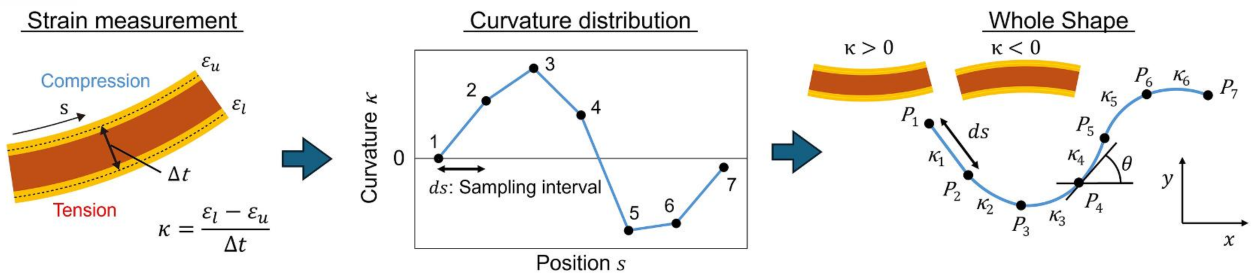

Figure 3. Shape reconstruction procedure [2] (the curvature, κ, is calculated from the strain difference between the upper and lower optical fibers, and the shape is reconstructed by connecting infinitesimal circular arcs with a radius of curvature of $1/\kappa$).

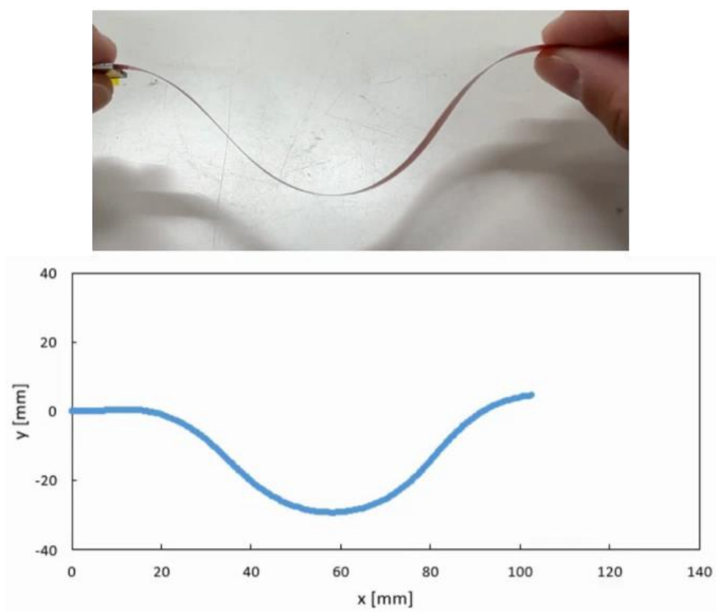

Figure 4. Shape comparison (top: deformed sensor configuration; bottom: real-time reconstructed shape).

The sensor shape can be reconstructed as follows (Fig. 3). First, the strain distribution along each optical fiber is measured using a distributed strain sensing system with a spatial resolution of approximately 1 mm, such as the Luna ODiSI system. The bending strain is calculated from the strain difference between the upper and lower fibers at each location, and the curvature distribution, κ, is subsequently obtained. The overall sensor shape is then reconstructed by smoothly connecting infinitesimal circular arcs with a radius of curvature equal to $1/\kappa$ (Fig. 4).

The principle of consolidation deformation monitoring is illustrated in Fig. 5. A sensor-shaped section is cut from the ply of interest, and the shape sensor is inserted into the resulting opening. Because the flexible sensor deforms together with the surrounding plies, continuous measurement of the sensor shape enables the deformation of the embedded ply to be tracked throughout the manufacturing process. Various materials can be used for the sensor substrate (i.e., thin plastic strip) depending on the application. When thickness uniformity is particularly important, a cured

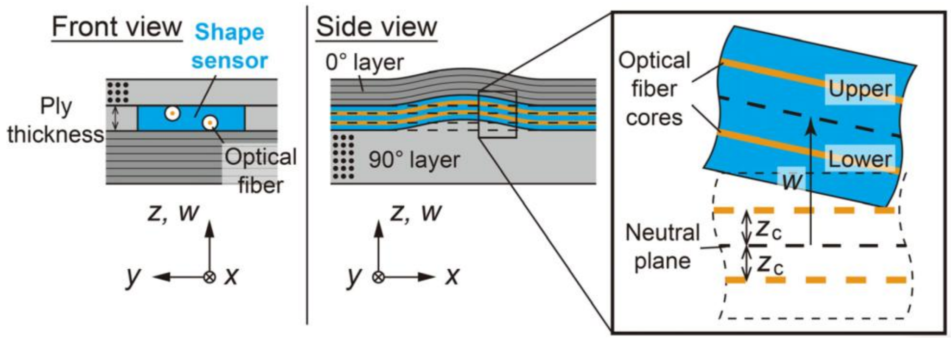

Figure 5. Principle of consolidation deformation monitoring [1] (the flexible shape sensor deforms together with the surrounding plies, enabling the deformation history of the embedded ply to be tracked through continuous shape measurement).

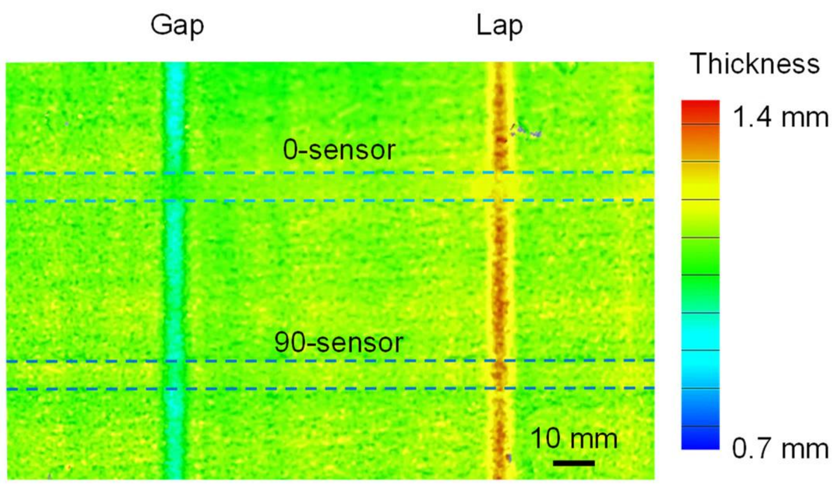

Figure 6. Thickness distributions around a gap/overlap region containing two sensors with different bending stiffnesses (Fig. 2) [1] (the high-stiffness 0-sensor suppresses consolidation deformation, resulting in the disappearance of the thickness variation associated with the gap/overlap).

prepreg of the target composite material can be employed to fabricate a sensor with the same thickness as the surrounding ply. The right side of Fig. 2 shows the cross-section of a sensor fabricated from a unidirectional CFRP prepreg. It should be noted that the sensor stiffness strongly depends on the substrate fiber orientation. Figure 6 compares the thickness distributions of laminates containing a high-stiffness 0-sensor, whose fibers are aligned with the sensor axis, and a low-stiffness 90-sensor, whose fibers are oriented transverse to the sensor axis, embedded in a gap/overlap region (Fig. 1). The high-stiffness 0-sensor suppresses consolidation deformation, resulting in the disappearance of the thickness variation associated with the gap/overlap. In contrast, the low-stiffness 90-sensor produces a thickness distribution nearly identical to that of a laminate without an embedded sensor. These results demonstrate that the use of a low-stiffness sensor is essential for minimizing disturbance to the consolidation deformation being measured.

3. Measurement Example: Specimens with Gaps of Various Widths [3]

As an example of consolidation deformation monitoring, specimens containing gaps with widths ranging from 1 mm to 3 mm were investigated. Figure 7 shows cross-sectional images of the cured specimens. As the gap width increases, the concave deformation formed in the plies above the gap becomes both deeper and wider. The deformation profiles measured by the shape sensor embedded in the upper ply agree closely with the observed cross-sectional geometries, demonstrating that the developed sensor can accurately capture consolidation deformation of less than 0.1 mm occurring over a region only a few millimeters wide. More importantly, the fiber-optic shape sensor can track the entire deformation history leading to the final cured shape. Figure 8 shows

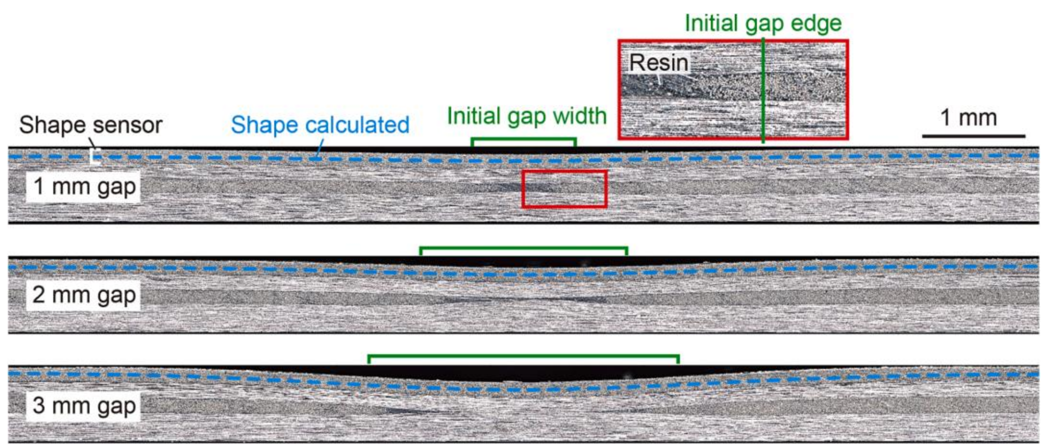

Figure 7. Measurement example for specimens with gaps of various widths [3] (the shape sensor was embedded in the upper ply and accurately captured consolidation deformation of less than 0.1 mm over a span of only a few millimeters).

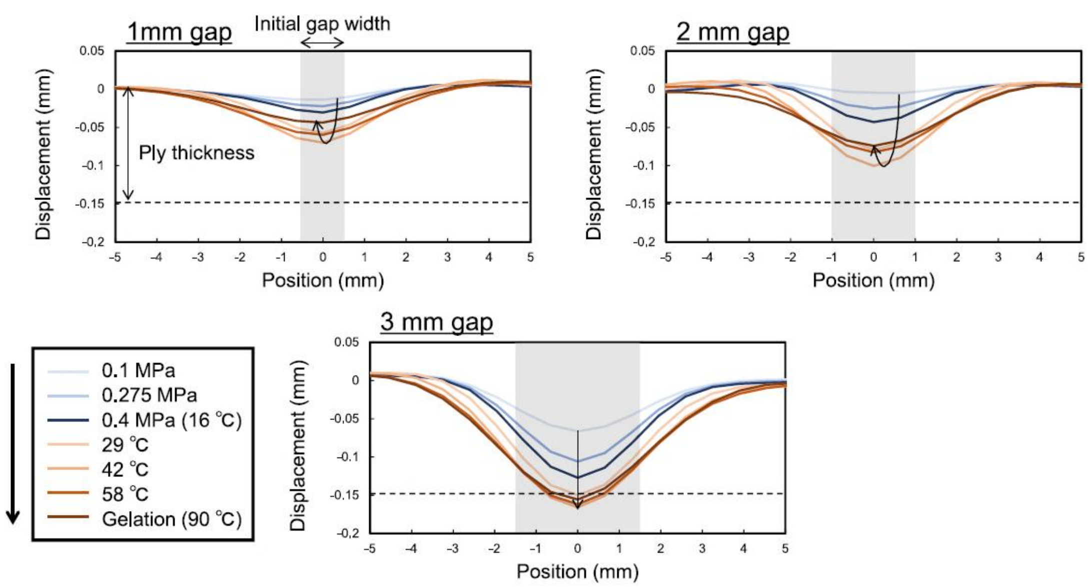

Figure 8. Consolidation deformation histories during pressurization and heating [3] (deformation partially recovered for narrow gaps, whereas it increased monotonically and then stabilized for wide gap).

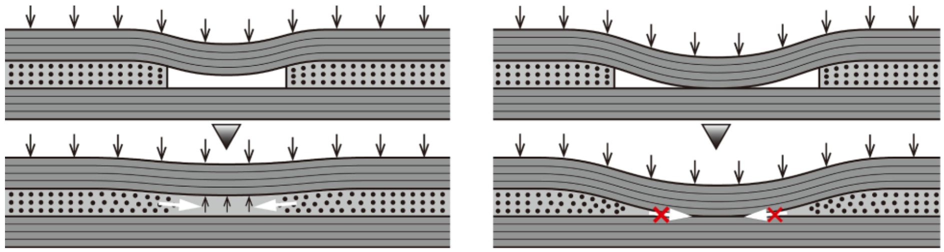

Figure 9. Consolidation deformation mechanisms for different gap widths [3] (left: resin and fibers flow into a narrow gap; right: a wide gap closes, preventing material inflow).

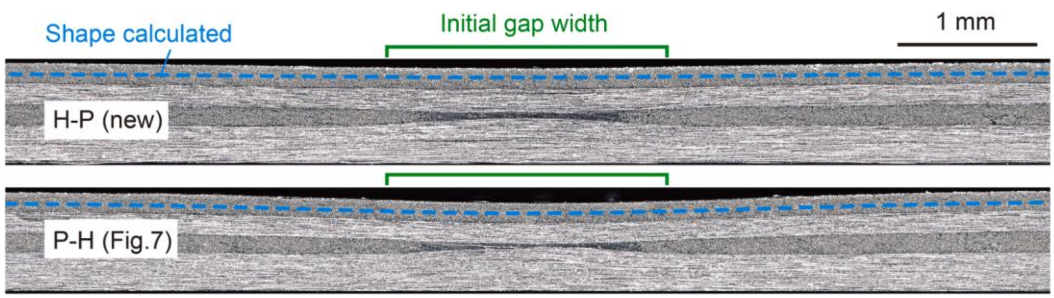

Figure 10. Suppression of consolidation deformation by process modification [3] (top: proposed heating–pressurization (H–P) process; bottom: conventional pressurization–heating (P–H) process).

the deformation histories measured during pressurization and heating in the autoclave. Distinct deformation behaviors were observed depending on the gap width. For the 3-mm gap specimen, the deformation increased monotonically during processing and ceased once the central deformation reached the gap depth and the gap was completely closed. In contrast, for the 1-mm and 2-mm gap specimens, the deformation never reached the full gap depth. Instead, after initially increasing, the deformation partially recovered during the latter stage of heating. The consolidation deformation mechanisms corresponding to different gap widths are illustrated in Fig. 9. For narrow gaps, the downward displacement of the upper ply is relatively small, allowing resin and fibers to flow into the gap region and push the upper ply upward. For wider gaps, however, the upper ply collapses sufficiently to close the gap, preventing further inflow of resin and fibers and thereby eliminating the upward support effect.

This observation represents the first direct evidence of a self-shape-recovery capability during composite manufacturing. To further enhance this recovery behavior, the manufacturing process was modified based on the deformation mechanisms shown in Fig. 9. In conventional composite processing, pressure is first applied to consolidate the laminate and eliminate interlaminar voids, followed by heating to cure the resin. However, the application of pressure causes the upper ply to collapse into the gap region (Fig. 8). To suppress this collapse, the sequence of pressurization and heating was reversed. By heating first, the resin viscosity is reduced, promoting the flow of resin and fibers into the gap region before pressure is applied. The resulting material accumulation supports the upper ply from below and mitigates its downward deformation. Figure 10 compares the consolidation deformation obtained using the conventional pressurization–heating (P–H) process and the proposed heating–pressurization (H–P) process. Compared with the conventional process, the proposed process significantly suppresses the collapse of the upper ply into the gap and results in a thicker resin-rich region within the gap, demonstrating the effectiveness of the proposed manufacturing strategy. In addition, the fiber-optic shape sensor enabled direct observation of how the proposed process suppressed consolidation deformation through continuous monitoring of the deformation history. These results demonstrate that the sensor is a versatile tool not only for elucidating consolidation mechanisms but also for evaluating process improvements and validating manufacturing simulations [4].

4. Other Applications

Consolidation deformation occurring during composite manufacturing is not limited to gap regions. For example, in corner regions, differences in surface area between the tool side and the outer surface generate non-uniform resin pressure within the laminate, resulting in thickness variations (Fig. 1(b)). In addition, wrinkles, i.e., out-of-plane fiber waviness, may form due to interlaminar gaps introduced during layup. The author research group has demonstrated that the fiber-optic shape sensor can also be used to monitor corner consolidation deformation associated with these manufacturing defects and to clarify the underlying deformation mechanisms [5-7]. Interestingly, a self-shape-recovery behavior similar to that observed in gap regions was also identified in these cases. This finding suggests that self-shape recovery is an intrinsic characteristic of composite materials and may provide a useful mechanism for achieving high-precision manufacturing.

The shape sensor has also been applied to thermoplastic composite stamp forming (Fig. 11), a manufacturing process expected to play an important role in next-generation aircraft because of

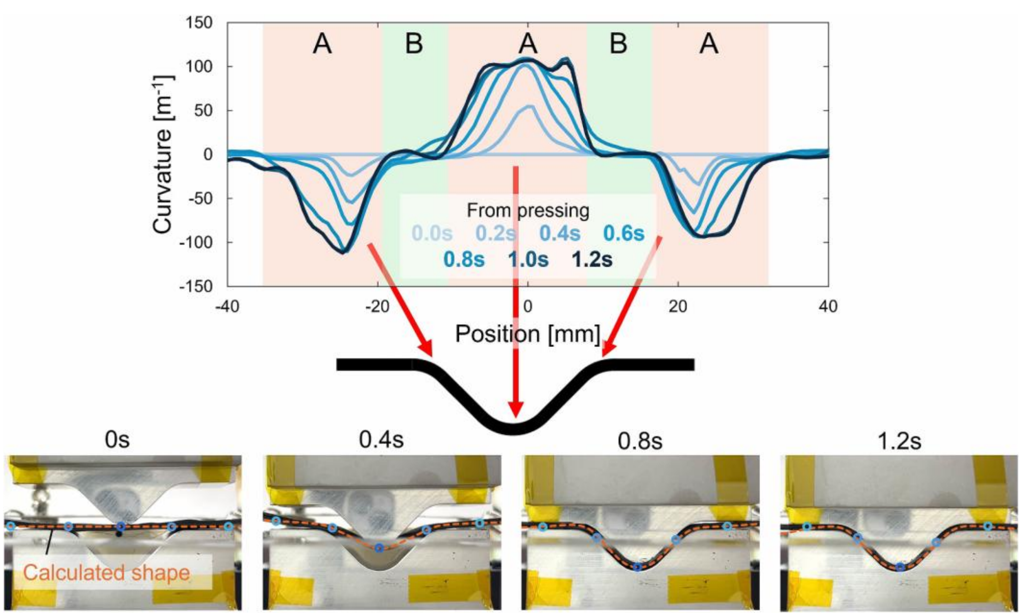

Figure 11. Application to thermoplastic composite stamp forming [2] (successful in-situ monitoring of the deformation of a flat composite blank during high-speed forming into a V-shaped geometry).

its potential for reducing production time [2]. In stamp forming, defects such as fiber waviness may occur depending on the press speed and material support conditions. The fiber-optic shape sensor has successfully measured deformation under these high-temperature and high-speed forming conditions, providing new insights into the forming mechanisms and their dependence on press speed. Based on this mechanistic understanding, efforts are currently underway to develop high-speed forming processes capable of producing defect-free components.

5. Summary

This paper introduced an embeddable strip-type fiber-optic shape sensor developed for monitoring consolidation deformation during composite manufacturing. A key feature of the sensor is its ability to visualize deformation inside an autoclave in real time, where direct observation has traditionally been difficult. The sensor can be used not only to characterize the evolution of consolidation deformation and clarify the underlying mechanisms, but also to optimize manufacturing conditions and validate numerical simulations. In recent years, increasing attention has been paid to the digitalization of manufacturing processes. However, such digitalization requires measurement technologies capable of capturing actual manufacturing phenomena. The proposed sensor represents a promising tool for monitoring composite manufacturing processes and is expected to find future applications in quality assurance, process optimization, and process control.

6. References

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