Static experimentations of the piezoceramic d_{15}-shear actuation mechanism for sandwich structures with opposite or same poled patches-assembled core and composite faces

Pelin Berika and Ayech Benjeddoub

*Institute of Technical Mechanics, Johannes Kepler University of Linz, Linz, Austria;
*Institut Supérieur de Mécanique de Paris (Supmeca), Paris, France

(Received 23 June 2011; final version received 25 August 2011)

Static d_{15}-shear actuated smart composites consisting of glass fiber/epoxy layers sandwiching piezoceramic shear patches-assembled cores were investigated experimentally and numerically. The piezoceramic cores were formed by connecting two or three patches with the same or opposite polarization directions. For each cantilevered benchmark the shear-induced transverse tip deflection, under increasing actuation voltage, ranging from 61.5 V to 198 V, was measured by an electronic speckle pattern interferometer system. The performance of the shear actuated smart composites was characterized by their shear-induced transverse deflection per length per voltage. It was found that this performance is much better at high voltages for which the response becomes nonlinear. For verification of the experimental results the proposed benchmarks were simulated within ABAQUS® commercial code using three-dimensional piezoelectric finite elements. The comparison of the obtained experimental and simulation results show a nonlinear dependence of the transverse deflection for voltages higher than around 92 V.

Keywords: piezoceramic d_{15}-shear; static actuation; smart composite

1. Introduction

Piezoceramic patches are known to be the most used active materials as transducers, sensors or actuators in the so-called smart structures technology; this is due in particular to their multi-mode response characteristics: (i) longitudinal response mode that uses the so-called d_{33} effect, (ii) transverse response mode that uses the so-called d_{31} effect, and (iii) thickness shear response mode that uses the so-called d_{15} effect. Compared to the former two modes, the latter is still the least investigated, as attested by its latest state of art analysis [1]. This survey indicates also that investigations of the shear response mode are mainly theoretical, either analytical or numerical. Hence, its experimentations are still rare compared to the other two response modes. Besides, the few available experiments have concerned mainly active or hybrid active–passive [2] vibration control; the only static experimentation mentioned in [1] has considered the bimorph configuration [3]. So, static experimentation of shear actuated multilayer structures is still needed; the main aim of this work was to fill this gap.
So far, piezoelectric actuation experimental characteristics have been analyzed either using direct current (DC static [4–6]) or alternative current (AC quasi-static [6,7]) actuations. The last technique requires low-frequency (first few Hz) dynamic measurements, whereas the former requires good preparation of the samples in order to avoid the so-called drift phenomena (slow increase of free strain after DC field application). Static strain and deflection are generally measured using light probes, as in [5], or strain gages, as in [6]. However use of the so-called electronic speckle pattern interferometry (ESPI) is becoming very popular for both conventional [8] and smart [9–11] structures. This is due in particular to the fact that the ESPI system provides more sensitive and full-range measurement possibilities than strain gages and has the advantage of being able to measure deformations and deflections of engineering structures and materials without contact. Hence, they do not change the response of the objects being studied, because of their non-contact nature. Therefore, results obtained by an ESPI system represent reality and can be used to validate analytical solutions. The visualization occurs in the form of fringes on the image. From the speckle patterns, the out-of-plane and the in-plane deformation can be determined. Digital image equipment processes the information included in the speckle patterns and displays the consequent interferogram on a computer monitor. The ESPI system can be used not only for one-step measurement but also for a series of measurements. For these reasons, the ESPI system was chosen for the static measurements described.

In the following sections, the experimental investigations conducted of \( d_{15} \)-shear actuated smart composites are first described in detail; they concern three benchmarks which differ by their lengths and also by the polarization configurations of the patches assembling the cores of the three sandwiches with composite faces. The three experimental benchmarks were numerically simulated using three-dimensional (3D) coupled piezoelectric finite element (FE) analysis using a commercial code. Finally, conclusions and perspectives close this presentation.

2. Experimental investigations of \( d_{15} \)-shear actuated smart composites

2.1. Experimental setup and benchmarks

The shear-induced transverse deflections of the cantilevered smart composites were detected as the \( z \)-component of the displacement and measured in an out-of-plane configuration by an ESPI system (Dantec-Ettmeyer ESPI Q300), as shown in the experimental setup of Figure 1. The other setup equipment included a high-voltage (HV) amplifier model T-502, a laboratory power supply type EA 3016, and an ISTRA data processing software for the control and evaluation of the ESPI system.

The materials used for the experimental benchmarks were PIC255 piezoceramic shear patches of dimensions \( 25 \times 25 \times 0.5 \) mm\(^3\) (from PI Germany) for the cores, and Polyspeed G-EV 760R glass fiber/epoxy layers (from Hexcel Austria) with 0.49 mm thickness for the sandwiching faces; the latter were cut to suitable dimensions for the benchmarks; then, the former were embedded between the latter using very thin methacrylate-based two-components adhesives.

Three types of experimental benchmarks were prepared; two of them have assembled cores from two patches so that they are 50 mm in length and 25 mm in width, while the third one has a core assembled from three patches so that it is 75 mm long with above width. One of the two short benchmarks has its piezoceramic shear core built by the connection of two oppositely poled (OP) shear patches, as shown in Figure 2a, while the piezoceramic
shear cores of the other benchmarks were constructed by the connection of two (Figure 2b) and three patches with same polarizations (SP).

The benchmarks were white colored (Figure 1b) so that the speckles occurring during an applied voltage could be better detected, and operated in room temperature.
2.2. **Experimental measurements**

For each benchmark a series of static shear-induced transverse deflection measurements were performed by the ESPI system at increasing voltages ranging from 65.1 V to 198 V. Figures 3a and 3b show the distributions of the speckle fringe patterns of the experimental benchmarks with, respectively, OP and SP two piezoceramic shear patches under 106 V. It is clear that these distributions differ, in particular at the interface between the patches, which is here located at the mid-lengths of the cores. This means that the OP core-based benchmark responds differently than the SP one. This chevron-like OP deformation can be exploited technologically to create a volume as for the valve-less shear-mode piezoceramic micro-pump described in [12].

When the applied voltage was increased the number of fringes also increased, as can be seen from Figures 4a and 4b for the SP three patches-assembled benchmark under 122 V and 194 V, respectively.

Figures 5a and 5b (respectively, Figures 6a and 6b or 7a and 7b), images obtained from ISTRA processing software, show, respectively, the surface distributions and along-length ($x$) variations of the transverse deflections of the smart composite with two OP (respectively, two SP or three SP) piezoceramic shear patches under 198 V and at the measurement coordinate $y = 14.44$ mm (respectively, $y = 15.12$ mm or $y = 9.06$ mm).

Since the length ranges of the benchmarks were not totally covered by the ESPI measurement system, the transverse deflections were measured near the free ends and approximated using the equation

![Figure 3. Speckle fringe patterns of the experimental benchmarks with two OP (a) and SP (b) shear patches under 106 V shear actuation.](image)

![Figure 4. Speckle fringe patterns of the experimental benchmark with three SP shear patches under 122 V (a) and 194 V (b) shear actuation.](image)
Figure 5. Experimental transverse deflection surface distribution (a) and variation along the x-axis (b), under 198 V shear actuation of the benchmark with two OP shear patches.

\[ u_{z,\text{max}} = \frac{u_{z,\text{meas}}}{x_2 - x_1} L, \]

where \( u_{z,\text{max}} \), \( u_{z,\text{meas}} \), \( x_1 \), \( x_2 \) and \( L \) are representing the benchmark actual maximum transverse deflection, maximum measured transverse deflection, the difference between the maximum and minimum measured at corresponding points in the axial x-direction and total length, respectively.
Figure 5b indicates that a change of the polarization directions of the integrated piezoceramic shear patches causes a change in the direction of the shear-induced deflection in the middle of the structure. It must be noted that the left and right shear-induced deflection lines in this figure are not totally symmetric and they have different slopes.

Figure 6. Experimental transverse deflection surface distribution (a) and variation along the x-axis (b), under 198 V shear actuation of specimen with two SP shear patches.
Figure 7. Experimental transverse deflection surface distribution (a) and variation along the x-axis (b), under 198 V shear actuation of the benchmark with three SP shear patches.

The (first) slope of the line in Figure 5b (respectively, Figure 6b or 7b) gives the so-called effective deflection which is defined as the shear-induced deflection per (half) length. The transverse shear deflection per (half) length per voltage is post-calculated by taking the difference between the minimum and maximum shear-induced deflection values given by ISTRA processing software and dividing it by the branding (half) length ($L$) of this
measurement and then by the applied voltage. This parameter is proposed as the main characterization factor for the actuation performance evaluation of the piezoceramic shear actuated smart composites.

The experimental results for the transverse deflection, effective transverse deflection and the proposed shear actuation performance indicator (effective transverse deflection per volt) values of the three benchmarks under three actuation voltages of 106 V, 108 V and 198 V are given in Tables 1, 2 and 3 for the two (OP and SP) short and the long (SP) benchmarks, respectively.

Results in Tables 1–3 prove the sensitivity of the ESPI system to the small deflections of these piezoceramic shear core-based sandwich smart composites.

The transverse deflection variations with the applied voltages are shown in Figures 8, 9 and 10 for the OP and SP two, and SP three patches-based specimens, respectively. These curves indicate that the $d_{15}$-shear actuated composite benchmarks responses are nonlinear,

| Table 1. Transverse deflection, effective transverse deflection and effective transverse deflection per volt values of the benchmark with two OP patches (OP-50mm). |
|-----------------------------------------------|
| **Applied voltage** | 198 V | 106 V |
| Experimental transverse deflection ($\times 10^{-6}$ m) | 3.27 | 1.55 |
| Experimental effective transverse deflection ($\times 10^{-6}$) | 131 | 62 |
| Experimental effective transverse deflection per volt ($\times 10^{-6}$/V) | 0.66 | 0.58 |
| FE Simulation transverse deflection ($\times 10^{-6}$ m) | 2.846 | 1.524 |
| FE Simulation effective transverse deflection ($\times 10^{-6}$) | 113.84 | 60.945 |
| FE Simulation effective transverse deflection per volt ($\times 10^{-6}$/V) | 0.575 | 0.575 |

| Table 2. Transverse deflection, effective transverse deflection and effective transverse deflection per volt values of the benchmark with two SP patches (SP-50mm). |
|-----------------------------------------------|
| **Applied voltage** | 198 V | 106 V |
| Experimental transverse deflection ($\times 10^{-6}$ m) | 6.6 | 3.55 |
| Experimental effective transverse deflection ($\times 10^{-6}$) | 132 | 71 |
| Experimental effective transverse deflection per volt ($\times 10^{-6}$/V) | 0.67 | 0.67 |
| FE Simulation transverse deflection ($\times 10^{-6}$ m) | 5.555 | 2.974 |
| FE Simulation effective transverse deflection ($\times 10^{-6}$) | 111.10 | 59.478 |
| FE Simulation effective transverse deflection per volt ($\times 10^{-6}$/V) | 0.561 | 0.561 |

| Table 3. Transverse deflection, effective transverse deflection and effective transverse deflection per volt values of the benchmark with three SP patches (SP-75mm). |
|-----------------------------------------------|
| **Applied voltage** | 198 V | 108 V |
| Experimental transverse deflection ($\times 10^{-6}$ m) | 9.07 | 4.35 |
| Experimental effective transverse deflection ($\times 10^{-6}$) | 121 | 58 |
| Experimental effective transverse deflection per volt ($\times 10^{-6}$/V) | 0.61 | 0.54 |
| FE Simulation transverse deflection ($\times 10^{-6}$ m) | 8.259 | 4.505 |
| FE Simulation effective transverse deflection ($\times 10^{-6}$) | 110.12 | 60.067 |
| FE Simulation effective transverse deflection per volt ($\times 10^{-6}$/V) | 0.556 | 0.556 |
Figure 8. Experimental vs. simulated transverse deflection of the benchmark with two OP patches.

Figure 9. Experimental vs. simulated transverse deflection of the benchmark with two SP patches.

Figure 10. Experimental vs. simulated transverse deflection of the benchmark with three SP patches.
in terms of the applied voltages, starting from 107 V for the OP-50mm, 91.5 V for the SP-50mm and 92.5 V for the SP-75mm benchmarks, respectively. This experimental non-linearity was already shown in the open literature for the extension (d_{31} effect) actuation mechanism (EAM) [4–7] and for the torsion actuation mechanism (TAM) [11], while it is shown here for the first time for the present shear actuation mechanism (SAM).

Finally, it can be concluded from Figures 8–10 and Tables 1–3 that the SAM has a good performance, but nonlinear response, at high actuation voltages and relatively low performance, but linear response, at low actuation voltages. These experimental results were subsequently verified by simulating the above three benchmarks using 3D FE within ABAQUUS® commercial code.

3. Finite element simulations of the experimental benchmarks

Numerical simulations of the above three experimental benchmarks of smart sandwich structures with d_{15}-shear cores and glass fiber/epoxy faces were conducted using ABAQUUS® FE commercial code. The static actuation analyses were made using C3D20E

![Figure 11](image.png)
and C3D20 piezoelectric and elastic quadratic (20 nodes) brick elements. The in-plane mesh had finite elements of size 1 mm, whereas that in the through-the-thickness had 1 and 2 elements for the glass fiber/epoxy and core layers, respectively. Hence, each smart composite benchmark of length 50 mm was modeled with 5000 elements and 32,816 nodes (Figures 11a and 11b), whereas that of length 75 mm was modeled with 7500 elements and 49,096 nodes (Figures 11c and 11d). The clamp was implemented by blocking the three translational displacements on the area situated at $x = 0$, which is perpendicular to the benchmarks major surfaces.

The opposite poling of the right piezoceramic shear patch of the first benchmark (Figure 2a) was implemented by changing the sign of the piezoceramic stress coupling constants to be negative. For this purpose, two different piezoelectric properties sets and sections are then assigned to the right and left piezoceramic shear patches. The piezoceramic and composite materials properties used are given in the Appendix.

The FE results corresponding to those provided in Figures 5, 6 and 7 are given, respectively, in Figures 12, 13 and 14. The latter indicate that there is a good qualitative correlation between experimental and numerical results. The slight difference near the

![Figure 12. FE simulated 3D deformation (a), shear deflection curve (b), and superposed x–z projections of the deformed and non-deformed configurations (c) of the benchmark with two OP piezoceramic shear patches (198 V actuation); clamped side is on the left.](image-url)
Figure 13. FE simulated 3D deformation (a) and the shear deflection (b) of the benchmark of length 50 mm with two SP piezoceramic shear patches (198 V actuation); clamped side is on the left.

clamp, between curves in Figures 12 and 13, and those in Figures 5 and 6, is due to the fact that the defined ESPI system measurement frames and the first measurement points, where the minimum transverse deflections occur, do not overlap on the physical clamp, but they are very near of it and the effect of the physical clamp can be still detected in the measurements. Since this minimum transverse deflection point does not consist of only one node as in the FE simulation, their images flat starting is longer, while in the FE curves of Figures 5 and 6, this can be seen only after zooming, since only one node is blocked along x-axis. The quantitative comparison for three actuation voltages (106 V, 108 V and 198 V) is provided in Tables 1, 2 and 3, where it can be seen that at low voltages experimental and FE simulation values correlate well, but not for higher actuation voltages (see tests discussion).

Simulations of the transverse deflections variations with the applied voltages are compared to the experimental ones in Figures 8, 9 and 10 for the OP-50mm, SP-50mm and SP-75mm cores-based sandwich smart composites, respectively. Starting from around 92 V for the SP cores and from 107 V for the OP core, these figures show deviations between experimental measurements and numerical simulations; after these threshold values, the experimental shear actuation response is nonlinear with regards to the applied high voltages, while the numerical response remains linear.
4. Conclusions and perspectives

The static shear-induced transverse deflections of piezoceramic $d_{15}$-shear actuated sandwich smart composites were measured by an electronic speckle pattern interferometer (ESPI) system for three benchmarks differing by their length (50 mm and 75 mm) and polarization directions (same or opposite) of the patches assembling the piezoceramic shear cores. The shear-induced transverse deflection per length per voltage is proposed as the performance evaluation criterion of the shear actuation mechanism (SAM). The experimental results proved that the ESPI system is a very sensitive tool for the measurement of small deflections of piezoceramic shear layer integrated composite structures. They also confirmed, as for the shear-induced torsion actuation mechanism, the nonlinear response of the SAM for high actuation voltages (here beyond around 92 V).

The experimental benchmarks were also simulated using three-dimensional piezoelectric finite elements (FE) within the ABAQUS® commercial code. Experimental and FE results show good agreement qualitatively and quantitatively, especially at low actuation voltages. However, the nonlinearity of the SAM observed during the experiments was not confirmed by the simulations, which showed a linear response.

As an immediate extension of the present work, experimental modal analyses of these benchmarks could be conducted [13], and SAM-based multi-core laminated smart composites could be investigated (in-progress). As another related perspective, the experiments-FE simulations discrepancy regarding the SAM observed nonlinear response merits further
investigations in the light of the approaches proposed in [14] and [15] that considered electric field nonlinear dependency of the piezoelectric coupling constants $d_{15}$ and $d_{31}$, respectively, or in [16] that considered geometric nonlinearity in the kinematics of the analytical model-based simulations.

Acknowledgements
Support of the authors from K2-Austrian Center of Competence in Mechatronics (ACCM) and from Dr. Michael Krommer, Institute for Technical Mechanics of the Johannes Kepler University at Linz (Austria), are gratefully acknowledged. The authors would like also to thank Prof. Helmut Rapp, Head of the Institute for Lightweight Structures of the Universität der Bundeswehr at München (Germany), for his help for the ESPI experiments, and Prof. Rudolf Wörndle, Head of the Institute for Designing Plastics and Composite Materials of the University of Leoben (Austria) for his support to the first author via the Polymer Competence Center Leoben.

References
[1] A. Benjeddou, *Shear-mode piezoceramic advanced materials and structures: a state of the art*, Mech. Adv. Mater. Struct. 14 (2007), pp. 263–275.
[2] M.A. Trindade, *Experimental analysis of active–passive vibration control using viscoelastic materials and extension and shear piezoelectric actuators*, J. Vib. Contr. 17 (2010), pp. 917–929.
[3] Q.M. Wang, B. Xu, V.D. Kugel, and L.E. Cross, *Characteristics of shear mode piezoelectric actuators*, Proc. 10th IEEE Trans. Int. Symp. Appl. Ferr. 2 (1996), pp. 767–770.
[4] I. Chopra, *Review of state of art of smart structures and intelligent systems*, AIAA J. 40 (2002), pp. 2145–2158.
[5] M. Yocum, H. Abramovich, *Static behavior of piezoelectric actuated beams*, Comput. Struct. 80 (2002), pp. 1797–1808.
[6] C. Maurini, *Piezoelectric composites for distributed passive electric control: beam modelling, modal analysis, and experimental implementation*, Ph.D. diss., Pierre & Marie Curie University, Paris, 2005.
[7] L.H. Kang, J.W. Lee, J.H. Han, S.J. Chung, and H.Y. Ko, *Development of a piezoelectric unimorph using a mechanically pre-stressed substrate*, Smart Mater. Struct. 18 (2009), 104007 (9pp).
[8] L. Yang, P. Zhang, S. Liu, P.R. Samala, M. Su, and H. Yokota, *Measurement of strain distributions in mouse femora with 3D-digital speckle pattern interferometry*, Optic Laser Eng. 45 (2007), pp. 843–851.
[9] D. Borza, D. Lemosse, and E. Pagnacco, *Full-field experimental–numerical study of mechanical strain and stress in piezoelectric multilayer compression-type actuators*, Compos. Struct. 82 (2008), pp. 36–49.
[10] P. Berik, H. Rapp, and R. Wörndle, *Experimental investigations of piezoelectric shear force actuated smart composites*, Proc. IV ECCOMAS Thematic Conf. Smart Struct. Mater., Porto, 2009.
[11] P. Berik and A. Benjeddou, *Piezoelectric $d_{15}$ shear response–based torsion actuation mechanism: an experimental benchmark and its 3D finite element simulation*, Int. J. Smart Nano Mater. 1 (2010), pp. 224–235.
[12] A. Benjeddou, C. Poizat, and M. Gall, *First use of the shear actuation mechanism for valve-less piezoelectric micro-pumps design*, Proc 8th Int. Conf. Comput. Struct. Tech., Las Palmas de Gran Canaria, 2006.
[13] P. Berik, M. Krommer, and A. Benjeddou, *Experimental evaluation of the electromechanical coupling of smart structures with $d_{15}$ shear-mode piezoceramic cores*, Proc. 22nd Int. Conf. Adapt. Struct., Corfu, 2011.
[14] M.A. Trindade and T.Y. Kakazu, *Structural control of sandwich beams using shear piezoelectric actuators subjected to large electric fields*, Proc. IV Congr. Nac. Eng. Mec. (CONEM), Recife, 2006.
[15] A. Chattopadhyay and C.E. Seeley, *A higher order theory for modeling composite laminates with induced strain actuators*, Compos. B: Eng. 28 (1997), pp. 243–252.

[16] L.Q. Yao, J.G. Zhang, L. Lu, and M.Q. Lai, *Nonlinear static characteristics of piezoelectric bending actuators under strong applied electric field*, Sensor Actuator: Phys. 115 (2004), pp. 168–175.

Appendix

Table A1. Material properties.

| Materials               | Constants                  | Notations | Values |
|-------------------------|----------------------------|-----------|--------|
| PIC255 (x-poled)        | Piezoelectric coupling    | $e_{15} = e_{24}e$ | 11.9   |
|                         | stress constants (C/m²)   | $e_{31} = e_{32}$ | $-7.15$ |
|                         | $e_{33}$                  |            | 13.7   |
| Dielectric constants    | $\varepsilon_{22} = \varepsilon_{33}$ | 8.234     |
| at constant strain (nF/m)| $\varepsilon_{11}$       | 7.588     |
|                         | $\varepsilon_{11}$       | 7.588     |
| Young's moduli (GN/m²)  | $E_2 = E_3$               | 62.89     |
|                         | $E_1$                     | 47.69     |
| Shear moduli (GN/m²)    | $G_{13} = G_{12}$         | 22.26     |
|                         | $G_{23}$                  | 23.15     |
| Poisson's ratios        | $\nu_{13} = \nu_{12}$    | 0.46      |
|                         | $\nu_{23}$                | 0.36      |
| Glass fiber/epoxy       | Mass density (kg/m³)      | $\rho$    | 7800   |
|                         | Young's moduli (GN/m²)    | $E_2 = E_3$ | 13.1   |
|                         | $E_1$                     | 33.11     |
| Shear Moduli (GN/m²)    | $G_{13} = G_{12}$         | 3         |
|                         | $G_{23}$                  | 2.3       |
| Poisson's ratios        | $\nu_{13} = \nu_{12}$    | 0.27      |
|                         | $\nu_{23}$                | 0.4       |
|                         | Mass density (kg/m³)      | $\rho$    | 2620   |